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THESIS

CALCULATION OF THE TRANSITION MATRIX FOR THE SCATTERING OF ACOUSTIC WAVES FROM A THIN ELASTIC SPHERICAL SHELL USING THE ATILA FINITE ELEMENT CODE

by

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March, 1994

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CONTENTS

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I. INTRODUCTION

The utilization of sonar systems in operations at sea depends on the ability to forecast their performance during the design and production phases of their development. For low frequency active sonar systems, arrays of large transducers are required to produce the necessary power output. Because of their size and power output, interactions among the elements of an array may need to be considered in modelling a given array.

Professors S. R. Baker of the Physics Department and C. L. Scandrett of the Mathematics Department of the Naval Postgraduate School are engaged in a joint research effort with the objective of developing the models necessary to predict the performance of arbitrary dense active sonar arrays.

The approach used in this research is based on the T-Matrix method. [Ref. 3].

The T-matrix method uses the superposition of spherical harmonics to represent the total radiated pressure from a transducer. The radiated pressure from one such transducer for each incoming harmonic will be

calculated in an effort to produce the transition matrix or T-matrix. The elements of the T-matrix may then used to calculate scattered pressures resulting from the interaction between transducers.

The T-matrix method is useful in computing the scattered pressure resulting from an arbitrary incident pressure on a given scatterer. This thesis is concerned with the application of the T-matrix method on an array of thin-shelled elastic spheres.

Once the theoretical results from scattering of spherical harmonics incident on a sphere have been obtained, the calculations from the T-matrix method can be compared for each harmonic with the computation from the Finite Element Code ATILA for the purpose of validation.

Furthermore, the acoustic impedance calculated from the thin shell theory (Chapter II) can be compared with the acoustic impedance computed by ATILA's results.

The remainder of this thesis is divided into five chapters. Chapter II describes the theory involved in the T-Matrix method, the Pritchard Approximation, the finite element analysis of a structure excited by an impinging wave, and the theory of forced vibration of a spherical shell. Chapter III describes the spherical model used in the ATILA code. Chapter

IV presents and discusses the results. Chapter V presents the conclusions. Appendix A contains a copy of the FORTRAN program used to generate the spherical harmonic impinging wave. Appendix B presents a copy of the code used in ATILA. Appendix C presents a FORTRAN code [Ref. 17] to calculate elements of the Transition Matrix.

II. THEORY

A. "T-MATRIX" METHOD

The "T-Matrix" method is a procedure for computing the acoustic field due to multiple radiating and/or scattering bodies. An outline is given below of how this method may be applied to compute the acoustic pressure due to a pair of piezoelectric spherical shell transducers.

If a voltage is applied to a thin piezoelectric spherical shell in a free-field environment, a displacement of the surface of the shell can be obtained by the canonical equations [Ref. 1]. This movement generates an acoustic pressure field in the surrounding medium. This is indicated in Figure 1 , where a sphere excited by a voltage V produces a radial velocity u over the surface of the sphere. The perturbation of the sphere on the environment yields a radiated pressure $p^R(r,\theta,\phi)$.

The acoustic pressure at a field point z , located at spherical coordinates r, θ, and ϕ, equals $p^R(r,\theta,\phi)$, since the sphere is in a free-field environment. Numerical values of $p^R(r,\theta,\phi)$ can be found by application of a finite-element analysis code such as ATILA [Ref. 2].

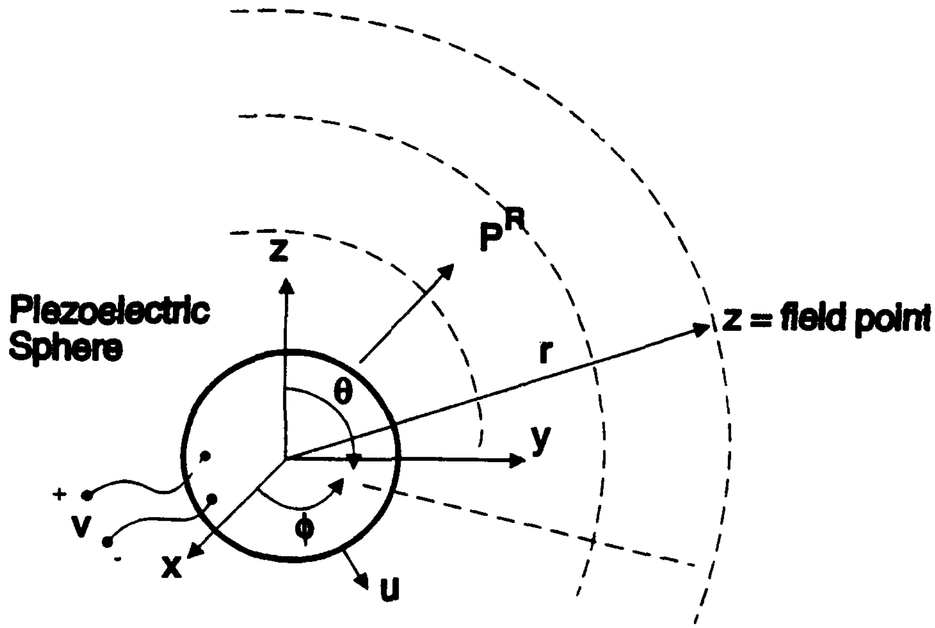

Figure 1. Single Radiation from a Piezolectric Sphere.

Next, consider the case of an array of two thin piezoelectric spherical shell transducers that are close enough to be considered "in the near field" of one another (see Figure 2).

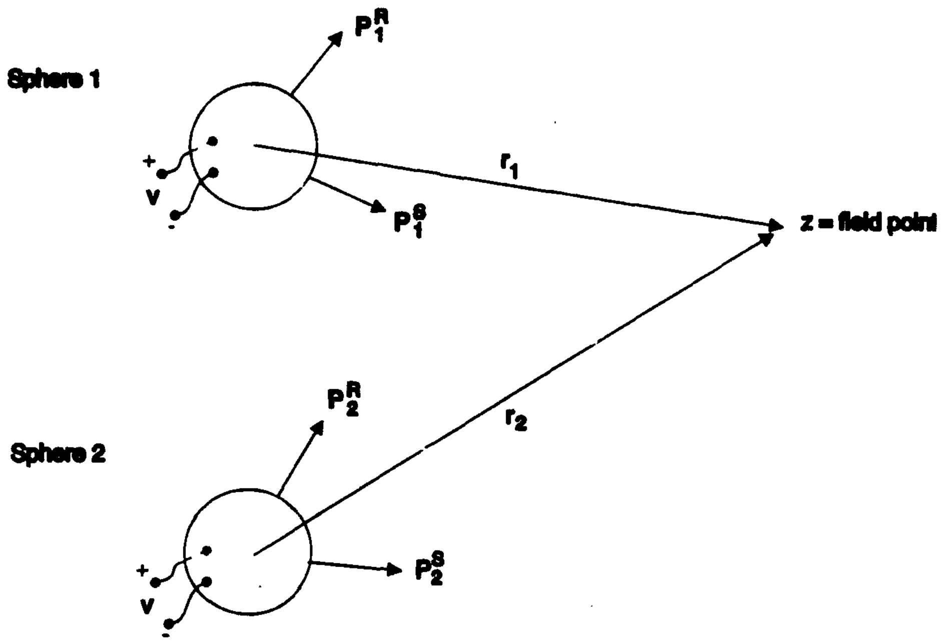

Figure 2. An Array of Two Thin Piezoelectric Spheres.

Outgoing waves at sphere 1 are composed of a radiated wave, p_1^R, resulting from the applied voltage V, and a scattered wave, p_1^S, due to the incident wave from sphere 2, p_1^I. The scattered pressure field can be mathematically represented by outgoing spherical Hankel functions and surface harmonics in the sphere 1 coordinate system as [Ref. 3]

$$p_1^S(r_1,\theta_1,\phi_1) = \Sigma_{n=0}^{\infty}\Sigma_{m=-n}^{n} P_{1nm}^S h_1^{(2)}(kr_1)P_n^m(\cos\theta_1)e^{im\phi_1} \tag{1}$$

where $h_n^{(2)}(kr_1) = j_n(kr_1) - iy_n(kr_1)$ is the Hankel function of the second kind (note that an $e^{i\omega t}$ harmonic time dependence has been assumed; for $e^{-j\omega t}$ harmonic time dependence $h_n^{(1)}(kr_1) = j_n(kr_1) + iy_n(kr_1)$ must be used instead

of $h^{(2)}$, P^S_{1nm} is the amplitude of the n, mth scattered wave component, k is the radial wave number, $P^m_n(\cos\theta_1)$ is the associated Legendre function, and

r_1, θ_1 and ϕ_1 are the spherical coordinates of the field point z with origin at

center of sphere 1. The radiated pressure field is similarly represented:

$$p^R_1(r_1,\theta_1,\phi_1) = \Sigma^{\infty}_{n=0}\Sigma^{n}_{m=-n} P^R_{1nm} h^{(2)}_n(kr_1) P^m_n(\cos\theta_1) e^{im\phi_1} \tag{2}$$

The incident pressure p^I_1 is assumed to be of the form:

$$p^I_1(r_1,\theta_1,\phi_1) = \Sigma^{\infty}_{n=0}\Sigma^{n}_{m=-n} P^I_{1nm}\, j_n(kr_1) P^m_n(\cos\theta_1) e^{im\phi_1} \tag{3}$$

This form is valid provided r_1 is less than the distance between the

origins of spheres 1 and 2.

By definition, the coeficients of the scattered pressure P^S_{1nm} are related to the coefficients of the incident pressure P^I_{1nm} by

$$\{P^S_1\} = [T]\{P^I_1\} \tag{4}$$

Where {} denotes a column vector of coefficients and [T] is the

so-called "transition matrix" or T-Matrix , a property of the transducer.

Similar expressions to the above apply to the corresponding fields on

sphere 2, i.e.,

$$p^S_2(r_2,\theta_2,\phi_2) = \Sigma\ ^{\infty}_{n=0}\Sigma\ ^{\infty}_{n=-n} P^S_{2nm} h^{(1)}_n(kr_2) P^m_n(\cos\theta_2) e^{im\phi_2} \tag{5}$$

$$\{P^s_2\} = [T]\{P^I_2\} \quad . \tag{6}$$

Note that it is assumed here for the sake of simplicity that the two transducers are identical, so that their T-matrices are also; in the general case this need not be so.

To proceed fruther it is necessary to be able to transform from one coordinate system into another. This is done using an "addition theorem", by which a spherical wave relative to one origin is expressed as a series of spherical waves relative to another [Ref. 3 and references therein]. Thus, for example, the incident pressure on sphere 1 can be expressed as the sum of the radiated and scattered pressures from sphere 2, transformed into the sphere 1 coordinate system using the addition theorem. In matrix form, this can be written

$$\{P_1^I\} = [G_{21}]\{P_2^R + P_2^S\}, \tag{7}$$

where $[G_{21}]$ represents the matrix of coefficients that transforms outgoing spherical harmonics at sphere 2 into standing wave spherical harmonics at sphere 1. Similarly, the incident pressure on sphere 2 is related to the radiated and scattered pressure on sphere 1 by

$$\{P_2^I\} = [G_{12}]\{P_1^R + P_1^S\}. \tag{8}$$

Using Equations (4) and (6) in Equations (7) and (8), we have a system of two equations in two unknowns:

$$\{P_1^S\} = [T][G_{21}]\{P_2^R + P_2^S\}, \tag{9}$$

$$\{P_2^S\} = [T][G_{12}]\{P_1^R + P_1^S\}. \tag{10}$$

Equations (9) and (10) may be written

$$\begin{bmatrix} I & -TG_{21} \\ -TG_{12} & I \end{bmatrix} \begin{Bmatrix} P_1^S \\ P_2^S \end{Bmatrix} = \begin{bmatrix} 0 & TG_{21} \\ TG_{12} & 0 \end{bmatrix} \begin{Bmatrix} P_1^R \\ P_2^R \end{Bmatrix} \tag{11}$$

where [I] is the identity matrix.

If $\{P_1^R\}, \{P_2^R\}$, and [T] can be found, such as by using the finite-element code ATILA, then, since $[G_{12}]$ and $[G_{21}]$ are known from the positions and orientations of the transducers through application of the addition theorem, the scattered pressures $\{P_1^S\}$ and $\{P_2^S\}$ can be determined. Then the resulting pressure at the field point z, p(z), is given by

$$p(z) = p_1^R(z_1) + p_1^S(z_1) + p_2^R(z_2) + p_2^S(z_2) \quad , \tag{12}$$

with the forms for the radiated and scattered pressure fields given previously, where z_i represents the coordinates of the field point z relative to the origin of the ith sphere.

The above development may be generalized to an array composed of an arbitrary number N of identical elements. For the ith element,

$$\{P_i^S\} = [T]\{P_i^I\}. \tag{13}$$

Here the scattered pressure from the ith transducer is represented. The components of the radiated pressure, P_{imn}^R, may be found using such a: ATILA finite-element code. Then the acoustic pressure at a field point z is the sum of the radiated and scattered pressures of each transducer.

$$p(z) = \Sigma_{i=1}^{N} [p_i^R(z_i) + p_i^S(z_i)] \quad . \tag{14}$$

B. THE "PRITCHARD APPROXIMATION"

The analytical calculation of mutual-radiation impedance, Z_{ij}, is made through the solution of the wave equation for the sound pressure produced by one transducer and by integrating that pressure over the radiating surface of another transducer [Ref. 4].

In Pritchard's original paper [Ref. 5], the mutual-radiation impedance was approximated for the case of flat circular pistons on an infinite rigid baffle. For small pistons and large separation, the Pritchard equation can be reduced to

$$Z_{12} = \frac{1}{2}(ka)^2\left(\frac{\sin kd}{kd} + i\frac{\cos kd}{kd}\right)\rho c A. \tag{15}$$

Here an $e^{-i\omega t}$ harmonic time dependance is assumed. This approximation neglects secondary scattered pressures.

It can be noted that Z_{12} has a real and an imaginary part,

$$Z_{12} = R_{12} + jX_{12} \ . \tag{16}$$

Here, Z_{12} is the mutual-radiation impedance between transducers 1 and 2, d is the distance between the centers of two transducers (see Figure 3), a is the piston radius, k is the acoustic wave number, ρc is characteristic impedance of the environment, and A is the area of the pistons.

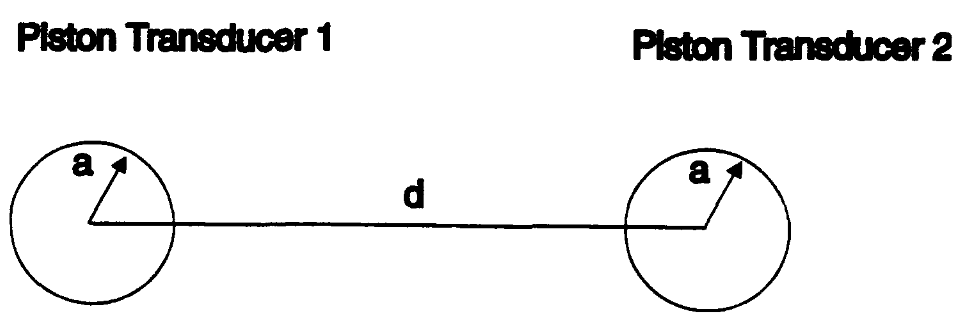

Figure 3. The Circular Pistons derived by Pritchard.

The self radiation resistance R_{ii}, for small ka, can be approximated by

$$R_{ii} = \tfrac{1}{2}(ka)^2 \rho c A. \tag{17}$$

The self radiation resistance is the real part of the transducer self-radiation impedance, written

$$\mathrm{Re}(Z_{self}) = \tfrac{1}{2}(ka)^2 \rho c A. \tag{18}$$

Therefore, for small ka, the mutual-radiation impedance can be expressed as

$$Z_{12} = \mathrm{Re}(Z_{self})\left(\frac{\sin kd}{kd} + i\frac{\cos kd}{kd}\right) = \mathrm{Re}(Z_{self})\frac{e^{ikd}}{kd}. \tag{19}$$

The so-called "Pritchard Approximation" refers to the application of Equation (19) to find the mutual radiation impedance of an array of identical transducers, not restricted to baffled pistons, i.e., Equation (19) has been applied to volumetric arrays. To calculate the mutual-radiation impedance, the wave number, the distance between transducers, and the self-radiation resistance of the transducer must be known in order to apply Pritchard's approximation.

C. THE ATILA CODE AND THE HARMONIC ANALYSIS

1. The Code

ATILA is a finite element code developed at Institut Superieur d'Electronique du Nord (ISEN) in France, and is intended for finite element analysis of underwater transducers. It uses the variational formulation of the governing mathematical equations of fluid-structure interactions [Refs. 6,7,8,9,10].

ATILA can solve a variety of problems, including: Static Analysis, Modal Analysis, and Harmonic Analysis.

Static Analysis yields the displacement field, the pressure field, and the electrical potential of an elastic or piezoelectric structure. Modal Analysis computes the eigenfrequencies and normal modes of an elastic, piezoelectric or magnetostrictive structure. Harmonic Analysis corresponds to a forced vibration problem where the excitation of the structure comes from an incident wave or from the voltage applied across the electrical terminals at a prescribed frequency. The analysis can be for a radiation or a scattering problem, for the given frequency in which the displacement field, electrical potential, electrical impedance of the structure, pressure field,

reflection and transmission coefficients, and transmitting voltage response are found.

For scattering problems, an incident wave is defined by the user. A default function is provided with ATILA which creates a plane wave traveling in the negative x axis direction. One can excite the structure with an arbitrary incident wave by adding a proper function at the end of the main FORTRAN program. Appendix A contains the FORTRAN program used to generate the incident spherical harmonic waves on the structure of the transducer.

ATILA calculates either the resulting "total pressure" or only the "scattered pressure." The total pressure, for the code, is the sum of the pressure generated by the electrical potential and the pressure of the scattered wave, plus the pressure of the impinging wave. In the case of scattered pressure, the pressure of the incident wave is not included .

The ATILA library has 46 different types of elements, used to model elastic, composite, piezoelectric, magnetostrictive, and magnetic materials as well as fluids, solid-fluid interfaces, and radiation dampers. Most of the elements use the same polynomial (quadratic) interpolation for both geometry and field variation (isoparametric elements).

2. Harmonic Analysis of an Elastic or Piezoelectric Structure

Excitation by an Impinging Wave

ATILA transforms equations of the Harmonic Analysis of a Radiating Piezoelectric Transducer into a matrix form. The motion equation is used for piezoelectric and elastic structures, Poisson's equation is used for piezoelectric material, and Helmholtz's equation is used for fluids [Ref. 2,11].

On the interfaces between the structure and the fluid, kinematics and dynamic continuity conditions hold under the assumption of no fluid cavitation at the fluid-structure interface. A radiation condition is applied to the external fluid boundary. Furthermore, to represent the condition of an impinging wave, the pressure and the flux fields are separated into incident and scattered parts.

In ATILA, the governing equations are written in matrix form as

$$\begin{bmatrix} [K_{uu}]-\omega^2[M] & [K_{u\phi}] & -[L] \\ [K_{u\phi}]^T & [K_{\phi\phi}] & [0] \\ -[L]^T & [0]^T & \frac{[H]}{A}-\frac{[M_1]}{B} \end{bmatrix} \begin{bmatrix} U \\ \Phi \\ P_{es} \end{bmatrix} = \begin{bmatrix} F-[L]P_i \\ -Q \\ \frac{1}{A}[G]P_{es}+\frac{\psi_i}{\rho\omega^2}+\left(\frac{[H]}{A}-\frac{[M]}{B}\right)P_i \end{bmatrix}$$

(20)

where:

U	:	vector of the nodal values of the components of the displacement field
Φ	:	vector of the nodal values of the electrical potential
P_i	:	vector of the nodal values of the incident pressure field
P_{es}	:	vector of the nodal values of the scattered pressure field
F	:	vector of the nodal values of the applied forces
Q	:	vector of the nodal values of the electrical charges
ψ_i	:	vector of the nodal values of the integrated normal derivative of the incident pressure on the surface boundary S (the externally applied pressure field is proportional to the externally applied flux)
K_{uu}	:	stiffness matrix
$[K_{u\phi}]$	:	piezoelectric matrix
$[K_{\phi\phi}]$	:	dielectric matrix
[M]	:	consistent mass matrix
$[M_l]$	:	consistent fluid (pseudo-) mass matrix
[H]	:	fluid (pseudo-) stiffness matrix
[L]	:	coupling matrix at the fluid structure interface (connectivity matrix)
[G]	:	complex linear operator that is frequency dependent
[0]	:	zero matrix
ω	:	angular frequency
ρ	:	fluid density
c	:	fluid sound speed
A	:	constant of the material
B	:	constant of the material
$[]^T$	:	the superscript T means the matrices transpose.

The incident flux field can be expressed with the nodal values of the incident pressure normal derivative,

$$\psi_i = [D]\frac{\partial P_i}{\partial n}. \tag{21}$$

Here, [D] is a matrix that the code dispenses for the damping elements.

The constants A and B are

$$A = \rho^2 c^2 \omega^2 \tag{22}$$

and

$$B = \rho^2 c^2 \ . \tag{23}$$

Note that ATILA assumes a harmonic time dependance of $e^{j\omega t}$. The incident pressure is provided by the user through a FORTRAN program (see Appendix A), and for each input frequency the code outputs the complex displacement, the complex pressure, rotational and electric potential fields at each node, and the complex electrical impedance and admittance. For a more detailed discusion of ATILA's operation, the reader is advised to consult the manual [Ref. 2].

D. FORCED VIBRATION OF A SPHERICAL SHELL.

1. Theory

The mathematical equations governing the true vibrations and deformation of thin elastic shells were first derived by Love in 1888 [Ref. 12]. It assumes the following postulates:

- The shell is thin, compared to the smallest radius of curve of shell
- Deflections of the shell are small, relative to the shell's thickness
- There is no transverse normal stress acting on planes parallel to the middle surface of shell
- There are no changes to the normals of the reference surface after and no changes in length during deformation

The equations are

$$u_{\theta\theta} + u_\theta \cot\theta + (1+\upsilon)w_\theta - u\cot^2\theta - \upsilon u - \tfrac{1}{2}(3-\upsilon)\frac{\cos\theta}{\sin^2\theta}v_\phi + \tfrac{1}{2}(1+\upsilon)\frac{1}{\sin\theta}v_{\theta\phi} +$$

$$\tfrac{1}{2}(1-\upsilon)\frac{1}{\sin^2\theta}u_{\phi\phi} = \frac{a^2}{C_p^2}u_{tt}, \tag{25}$$

$$\tfrac{1}{2}(1-\upsilon)[v_{\theta\theta} + v_\theta\cot\theta] + \tfrac{1}{2}(1-\upsilon)(2-\csc^2\theta)v + (1+\upsilon)\frac{1}{\sin\theta}w_\theta + \tfrac{1}{2}(3-\upsilon)\frac{\cos\theta}{\sin^2\theta}u_\phi +$$

$$\frac{1}{\sin^2\theta}v_{\phi\phi} + \tfrac{1}{2}(1+\upsilon)\frac{1}{\sin\theta}u_{\phi\theta} = \frac{a^2}{C_p^2}v_{tt}, \tag{26}$$

and

$$-(1+\upsilon)[u_\theta + u\cot\theta + \frac{1}{\sin\theta}v_\phi + 2w] + \frac{(1-\upsilon^2)}{Eh}a^2\sigma_a = \frac{a^2}{C_p^2}w_{tt}, \tag{27}$$

where the subscripts θ, φ, and t indicate partial differentiation and

ν : Poisson's ratio.
h : shell thickness.
C_p : shell's "plate" velocity.
E : Young's modulus.
σ_a : outward normal stress applied to shell.
a : spherical shell radius.
θ,φ,ρ : spherical coordinates (see Figure 1).
u,v,w : components of displacement (see Figure 4).

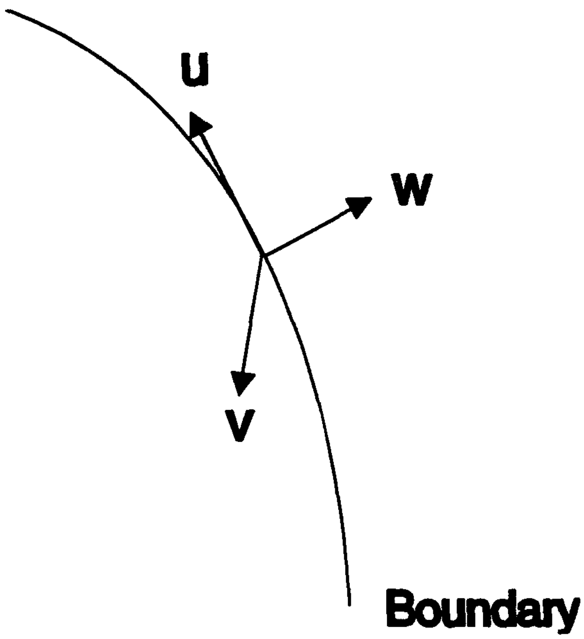

Figure 4. Components of Displacement.

To calculate the shell's plate velocity, C_p,

$$C_p = \sqrt{\frac{E}{\rho_s(1-\upsilon^2)}}\ \text{m/s} \tag{27}$$

is used [Ref.1].

Here, ρ_s is the density of shell's material.

By a series of manipulations detailed in Love's work, u and v are eliminated from the three equations, resulting in

$$w_{\theta\theta} + \cot\theta w_\theta + \left[\frac{(\Omega^2+1-\upsilon)[\Omega^2-2(1+\upsilon)]}{\Omega^2-(1-\upsilon^2)} - \frac{m^2}{\sin^2\theta}\right]w =$$

$$\frac{-a^2}{Eh[\Omega^2-(1-\upsilon^2)]}\left\{\sigma_{a\theta\theta} + \sigma_{a\theta\theta}\cot\theta + (\Omega^2 + 1 - \upsilon - \frac{m^2}{\sin^2\theta})\sigma_a\right\}, \tag{28}$$

where the frequency dependent term, Ω, is

$$\Omega = \frac{\omega a}{C_p}, \tag{29}$$

and all ϕ dependence is of the form $e^{im\phi}$. A harmonic time dependance of the form $e^{i\omega t}$ has been assumed.

Here,

$$\omega = 2\pi f, \tag{30}$$

and f is the excitation frequency.

If the new independent variable η is introduced:

$$\eta = \cos\theta. \tag{31}$$

The derivations with respect to θ can be replaced by

$$\frac{\partial}{\partial\theta} = -\sqrt{1-\eta^2}\,\frac{\partial}{\partial\eta}, \tag{32}$$

and

$$\frac{\partial^2}{\partial\theta} = -\eta\frac{\partial}{\partial\eta} + (1-\eta^2)\frac{\partial^2}{\partial\eta^2}. \tag{33}$$

Writing Equation (28) in terms of (32) and (33):

$$(1-\eta^2)w_{\eta\eta} - \eta w_\eta + \frac{\eta}{\sqrt{1-\eta^2}}(-\sqrt{1-\eta^2}\,w_\eta)$$

$$+\left[\frac{(\Omega^2+1-\upsilon)\,[\Omega^2-2\,(1+\upsilon)]}{\Omega^2-(1-\upsilon^2)} - \frac{m^2}{1-\eta^2}\right]w =$$

$$\frac{-a^2(1-\upsilon^2)}{Eh[\Omega^2-(1-\upsilon^2)]}\times$$

$$\left[-(1-\eta^2)\sigma_{a\eta\eta} - \eta\sigma_{a\eta} + \frac{\eta}{\sqrt{1-\eta^2}}(-\sqrt{1-\eta^2}\,\sigma_{a\eta}) + \left\{(\Omega^2+1-\upsilon) - \frac{m^2}{1-\eta^2}\right\}\sigma_a\right.,$$

(34)

and it can be seen that w and σ_a are being operated on by Legendre's differential equation.

Representing the applied stress σ_a, and the normal component, w, in terms of the Legendre polynomial yields

$$w = \Sigma_{n,m} w_{nm} P_n^m(\eta) e^{im\phi} \tag{35}$$

and

$$\sigma_a = \Sigma_{n,m} F_{nm} P_n^m(\eta) e^{im\phi}, \tag{36}$$

where $P_n^m(\eta)$ are the associated Legendre eigenfunctions weighted by the excitation stress amplitude F_{nm} and the normal displacement amplitude w_m. Legendre's equation can be written

$$(1-\eta^2)\frac{\partial^2}{\partial\eta^2}P_n^m(\eta) - 2\eta\frac{\partial}{\partial\eta}P_n^m(\eta) - \frac{m^2}{1-\eta^2}P_n^m(\eta) = -\lambda_n P_n^m(\eta), \tag{37}$$

where

$$\lambda_n = n(n+1). \tag{38}$$

and by substitution of (36) and (37) into (40) using (39), one is left with the algebraic equation related F_{nm} to w_{nm}:

$$\left\{\frac{(\Omega^2+1-\nu)\,[\Omega^2-2\,(1+\nu)]}{\Omega^2-(1-\nu^2)} - \lambda_n\right\} w_{nm} = \frac{-a^2}{hC_p^2\rho_s[\Omega^2-(1-\nu^2)]}[\Omega^2+1-\nu-\lambda_n]F_{nm} \quad . \tag{39}$$

In analogy with mechanical impedance [Ref. 13], the modal mechanical impedance, Z_n, can be defined as:

$$Z_n = \frac{F_{nm}}{i\omega w_{nm}}, \tag{40}$$

where the time dependence is given by $e^{-i\omega t}$.

It is then possible to write Equation (40) with modal mechanical impedance, as

$$Z_n = i\frac{hC_p\rho_s}{a\Omega}\left\{\frac{[\Omega^2-2(1+\upsilon)](\Omega^2+1-\upsilon-\lambda_n)-\lambda_n(1+\upsilon)^2}{\Omega^2+1-\upsilon-\lambda_n}\right\}. \tag{41}$$

Now, for the scattering problem, the pressure directed radially inward will be the sum of the incidental spherical wave and the outgoing spherical wave.

$$F_{nm} = -\left\{j_n(ka)I_{nm} + h_n^{(2)}(ka)R_{nm}\right\}, \tag{42}$$

where the term $j_n(ka)I_{nm}$ refers the incident spherical wave, p^i, and the term $h_n^{(2)}(ka)R_{nm}$ is the scattered spherical wave, p^s. The constants I_{nm} and R_{nm} are amplitudes of incident and scattered waves respectively.

$$p^i = \Sigma_{nm} I_{nm}\, j_n(kr)P_n^m(\eta)e^{im\phi}, \tag{43}$$

$$p^s = \Sigma_{nm} R_{nm} h_n^{(2)}(kr)P_n^m(\eta)e^{im\phi}, \tag{44}$$

$$w = \Sigma_{nm} w_{nm} P_n^m(\eta) e^{im\phi}. \tag{45}$$

Equations (43), (44), and (45) express the pressures and radial displacements in terms of spherical harmonics.

Applying Equation (42) in Equation (40) yields

$$I_{nm}\, j_n(ka) + R_{nm} h_n^{(2)}(ka) = -i\omega Z_n w_{nm}. \tag{46}$$

Furthermore, applying Euler's Equation [Ref. 13] at the surface of sphere,

$$\frac{\partial p}{\partial r}\Big\rfloor_{r=a} = -\rho_f \frac{\partial^2 w}{\partial t^2}\Big\rfloor_{r=a}. \tag{47}$$

where, ρ_f is the density of the fluid.

The pressure at surface, p, is the sum of the incident pressure, p^i, and the scattered pressure, p^s, as in

$$p = p^i + p^s. \tag{48}$$

Now, applying Equations (43), (44), (45) and (46) on (47),

$$I_{nm}\, j'_n(ka) + R_{nm} h_n^{(2)\prime}(ka) = \omega \rho_f C_f w_{nm}. \tag{49}$$

where $j_n'(ka)$ and $h_n^{(2)\prime}(ka)$ are the first derivatives of the spherical Bessel and Hankel functions.

From Equation (49),

$$w_{nm} = \frac{1}{\omega\rho_f C_f}\left\{I_{nm}\, j_n'(ka) + R_{nm} h_n^{(2)\prime}(ka)\right\}. \tag{50}$$

Now, Equation (50) can be utilized in Equation (46), yielding

$$\rho_f\, C_f\, [I_{nm}\, j_n(ka) + R_{nm} h_n^{(2)}(ka)] = -iZ_n [I_{nm}\, j_n'(ka) + R_{nm} h_n^{(2)\prime}(ka)]. \tag{51}$$

Finally, we have an equation for calculation of the constant term R_{nm},

$$R_{nm} = -\left\{\frac{iZ_n j_n'(ka) + \rho_f C_f j_n(ka)}{iZ_n h_n^{(2)\prime}(ka) + \rho_f C_f h_n^{(2)}(ka)}\right\} I_{nm} \tag{52}$$

The values of R_{nm} for each n and m will be the diagonal elements of the T-matrix of the thin spherical shell; each I_{nm} equals one.

2. Thinness Criteria

The theory of thin elastic shells is based upon the postulate that shells are thin. No exact definition of thinness is available, however.

From Junger & Feit [Ref. 14] we have a definition of "thick" plates, expressed as

$$h > \frac{\lambda_s}{20}, \tag{53}$$

where λ_s is the shear wavelength. An ad hoc treatment to account for thick shells that takes into account bending stresses introduces the parameter β,

which is a function of the thickness, h, and the middle surface of the shell, a_m, as in

$$\beta^2 = \frac{h^2}{12a_m^2}. \tag{54}$$

A rule of thumb suggested by Kraus [Ref. 15], is that the thickness should be less than one tenth of the radius of curvature of the reference surface, i.e., $\beta^2 < 1/1200$.

On the other hand, when Kraus examines the dynamic analysis of shells [Ref. 15], he affirms that the theory based upon Love's postulate gives a reliable result in the range

$$0 < \Omega < \Omega_s, \tag{55}$$

where Ω_s is the dimensionless frequency of the first thickness shear mode:

$$\Omega_S = \frac{\omega_S a_m}{C_T}, \tag{56}$$

where

$$\omega_s = \frac{\pi C_T}{h}, \tag{57}$$

and

$$C_T = \left(\frac{E}{2(1+\upsilon)\rho_s}\right)^{\frac{1}{2}}. \tag{58}$$

Applying Equation (27) and (29) in Equation (55) yields

$$0 < \sqrt{\frac{\rho_s(1-\upsilon^2)}{E}}\,\omega a_m < \frac{1}{10}\sqrt{\frac{\rho_s(1-\upsilon^2)}{E}}\,\omega_s a_m. \tag{59}$$

Now, after simplifying Equation (59) and substituting Equation (57),

$$0 < \omega < \frac{2\pi C_T}{20h}, \tag{60}$$

which can be rewritten as

$$h < 0.05\lambda_s, \tag{61}$$

and is exactly the same definition offered by Junger & Feit [Ref. 14] listed in Equation (53).

At this point, the thinness criterion for applying the theory of thin elastic shell can be considered to be the expression in Equation (61). This criterion is obeyed in all subsequent calculations.

III. SPHERICAL THREE-DIMENSIONAL MODEL

A. INTRODUCTION

In order to apply the T-matrix method to modeling a dense sonar array, the radiated and scattered pressure from an individual transducer must be calculated. Using finite element analysis, the pressure scattered from a transducer due to an incident spherical harmonic wave can be computed very accurately. To employ the Finite Element Code ATILA, a three-dimensional model of an elastic spherical shell is used.

B. THE MODEL

A 0.5 m outer radius, one centimeter-thick spherical steel shell in water is modeled. An ATILA model is realized using 3D elastic elements, 3D fluid elements, 2D solid-fluid interface elements, and 2D radiation surface elements. The thickness was chosen in an attempt to comply with aspect ratio constraints [Ref. 2] for elements used by ATILA, and to be within the theoretical conditions of thinness (Chapter II).

In order to calculate the limit of thickness to which we can apply the theory of thin elastic shells (Chapter II), the following parameters of the model (for steel) are applied in Equation (58)

$E = 0.125 \times 10^{12}$ (Young's modulus)

$\rho_s = 7500\ Kg/m^3$, and

$\upsilon = 0.33$ (Poisson's ratio).

The value of C_T is then 3282.83 m/sec^2, which for a chosen operating frequency of 474 Hz (corresponding to ka=1) results in an upper limit for the shell thickness of 0.346 m, and therefore a thickness of one centimeter is verifiably inside the limit.

The complete ATILA code for the elastic shell is presented in Appendix B. Note that, to write an ATILA code for a piezoelectric sphere, the same model can be used as for the elastic sphere. In this instance, the ATILA code can handle the piezoelectric sphere by changing the elements from elastic to piezoelectric type.

The model is composed of 2746 nodes and 288 elements. The mesh is shown in Figures 5 and 6.

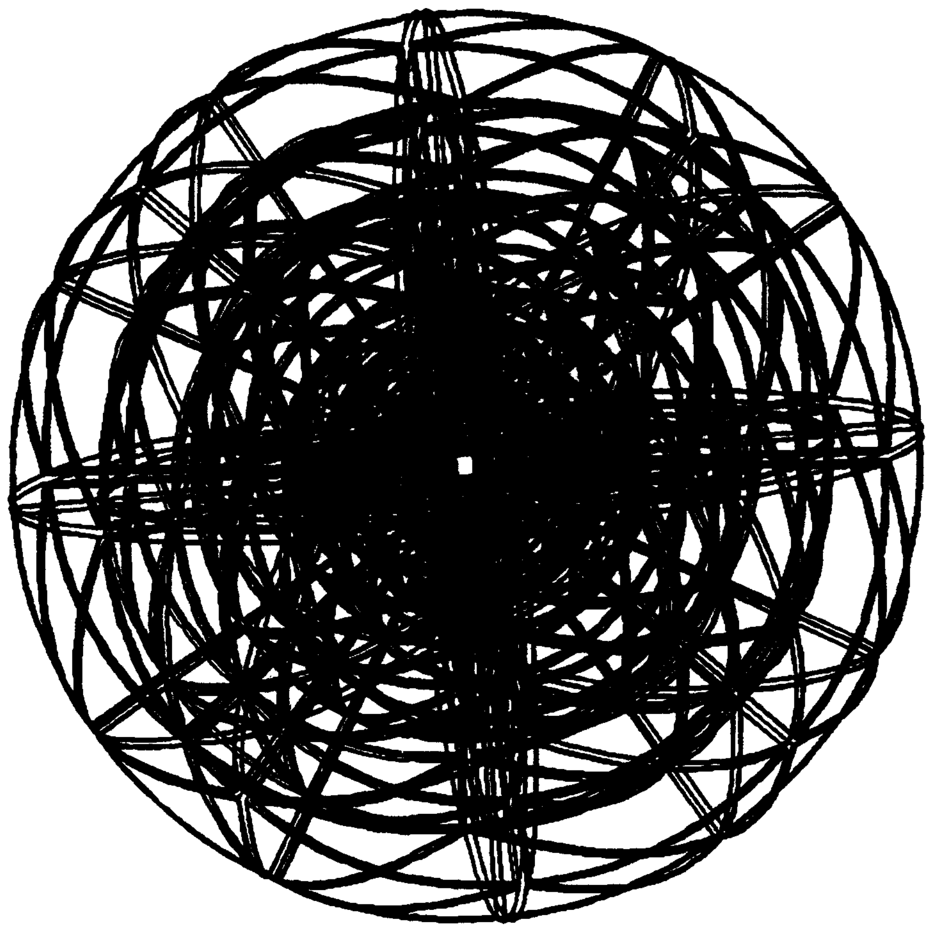

Figure 5. The Model, as Seen from the Side.

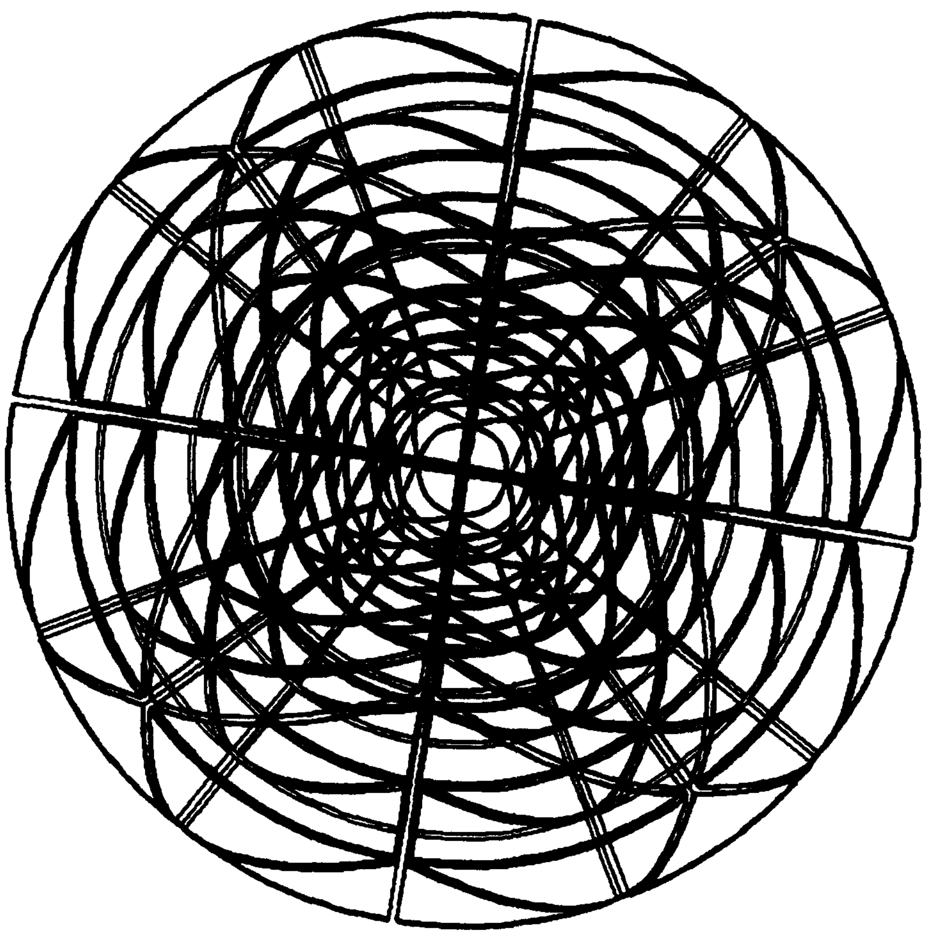

Figure 6. The Model, as Seen from Above.

The material properties of the shell are listed on the first page of Appendix B. The format is described in the ATILA user's manual [Ref. 2].

The elements used in the model followed the pattern from the manual [Ref. 2], and are presented in Table 1.

TABLE I. ATILA ELEMENTS		
Region	Element	Geometry
Elastic shell	SHEL06C	6-node triangular
Interface solid - fluid	TRIA12I	12-node triangular
Fluid	PRIS15F	15-node triangular prism
Radiation Surface	TRIA06R	6-node triangular

IV. RESULTS

A. THE T-MATRIX ELEMENTS AND THE ATILA CODE.

The definition of the T-matrix adopted in this work relates outgoing spherical waves (i.e. Hankel functions) to incident standing waves (i.e., spherical Bessel functions). However, using ATILA, calculation of the coefficients of the scattered pressure for each harmonic, $\{P^s\}$, requires that the incident wave [Appendix A] be an incoming traveling wave rather than a standing wave.

To use the results of the ATILA code in calculations, Equation (46) and its respective derivative, Equation (49) is adapted to

$$\overline{I_{nm}}\, h_n^{(1)}(ka)+\overline{R_{nm}}\, h_n^{(2)}(ka) = -i\omega Z_n\, \overline{W_{nm}}, \tag{62}$$

and its first derivative,

$$\overline{I_{nm}}\, h_n^{(1)\prime}(ka)+\overline{R_{nm}}\, h_n^{(2)\prime}(ka) = \omega\rho_f C_f\, \overline{W_{nm}}. \tag{63}$$

The coefficients $\overline{R_{nm}}$ are the amplitudes of the scattered wave components and the coefficients $\overline{W_{nm}}$ are the amplitudes of the components

of the radial displacement coefficients for an incoming wave with coefficients $\overline{I_{nm}}$.

Equation (52) (Chapter II) is used to calculate the R_{nm} coefficients from an incident standing wave, from where the T-Matrix elements are obtained. For incident incoming traveling waves, the R_{nm} elements can be calculated as follows.

From Equation (62) and (63),

$$\overline{R_{nm}} = -\left\{ \frac{iZ_n h_n^{(1)'}(ka) + \rho_f C_f h_n^{(1)}(ka)}{iZ_n h_n^{(2)'}(ka) + \rho_f C_f h_n^{(2)}(ka)} \right\} \overline{I}_{nm}. \tag{64}$$

We can relate R_{nm} and $\overline{R_{nm}}$. We, first ,define :

$$X_{nm} = -\left\{ \frac{iZ_n(i\, y_n'(ka)) + \rho_f C_f (i\, y_n(ka))}{iZ_n h_n^{(2)'}(ka) + \rho_f C_f h_n^{(2)'}(ka)} \right\} I_{nm}, \tag{65}$$

where $y_n(ka)$ is the spherical Bessel function of the second kind.

Applying Equation (65) on Equations (52) and (64), respectively :

$$R_{nm} - X_{nm} = -1 \tag{66}$$

and

$$\overline{R_{nm}} - X_{nm} = R_{nm} \tag{67}$$

Solving Equations (66) and (67) in terms of R_{nm}:

$$R_{nm} = \tfrac{1}{2}\{\overline{R_{nm}} - 1\} \tag{68}$$

Equation (68) is used to calculate the R_{nm} coefficients, and hence the T-Matrix elements for incident standing waves, from the $\overline{R_{nm}}$ coefficients calculated when ATILA code uses incoming incident waves to compute the scattered pressure.

The goal of this research is to compare the T-Matrix elements computed by scattered field pressure from the ATILA code with those determined by theoretical means (Appendix C).

The T-Matrix for an elastic spherical shell is a diagonal matrix where the non-zero elements equal the R_{nm} coefficients, for $I_{nm} = \overline{I_{nm}} = 1$. In this research, calculations of $\overline{R_{nm}}$ were performed up to the harmonic of second order, and the T-Matrix has the following format:

$$\begin{pmatrix} R_{00} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_{1-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_{10} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{2-2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{2-1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_{20} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{21} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{22} \end{pmatrix}$$

In the T-matrix, for instance, the element R_{2-1} corresponds to the spherical harmonic with n equal to two and m equal to negative one. The

T-Matrix elements were theoretically computed using thin shell theory (Appendix C) and the results are presented in Table II.

TABLE II. THE ANALYTIC DIAGONAL ENTRIES OF THE T-MATRIX				
ELEMENT	REAL PART	IMAG PART	MAGNITUDE	PHASE (DEGREES)
$T_{11}=R_{00}$	-1.3465E-02	1.1525E-01	1.1604E-01	9.6663E+01
$T_{22}=R_{1-1}$	-6.0255E-03	7.7390E-02	7.7624E-02	9.4452E+01
$T_{33}=R_{10}$	-6.0255E-03	7.7390E-02	7.7624E-02	9.4452E+01
$T_{44}=R_{11}$	-6.0255E-03	7.7390E-02	7.7624E-02	9.4452E+01
$T_{55}=R_{2-2}$	-6.1773E-04	-2.4847E-02	2.4854E-02	-9.1424E+01
$T_{66}=R_{2-1}$	-6.1773E-04	-2.4847E-02	2.4854E-02	-9.1424E+01
$T_{77}=R_{20}$	-6.1773E-04	-2.4847E-02	2.4854E-02	-9.1424E+01
$T_{88}=R_{21}$	-6.1773E-04	-2.4847E-02	2.4854E-02	-9.1424E+01
$T_{99}=R_{22}$	-6.1773E-04	-2.4847E-02	2.4854E-02	-9.1424E+01

Incident waves of the form

$$P_{inc}(r,\theta,\phi) = h_n^{(1)}(kr)P_n^m(\cos\theta)e^{im\phi}e^{iwt}$$

[Appendix A] for particular values of *n* and *m* were applied to the finite-element model spherical shell using the ATILA code and the resulting scattered pressures were calculated . For each incident wave of a particular spherical harmonic component (one *n* and *m*), the resulting reflection coefficients for all the spherical harmonic components (all *n* and *m*) were calculated from nodal values of the scattered pressure on the shell surface by a least-squares fitting procedure employing singular value decomposition

[Appendix C]. The results for the diagonal elements of the T-matrix are given in Table III. The last two columns of Table III give the error in the ATILA results for the diagonal components compared to the theoretical results of Table II.

TABLE III. THE ATILA DIAGONAL T-MATRIX ELEMENTS						
ELEMENT	REAL PART	IMAG PART	MAGNITUDE	PHASE (DEGREES)	MAG. ERROR (PERCENT)	PHASE ERROR (DEGREES)
T_{11}	-1.2624E-02	1.1429E-01	1.1498E-01	9.6303E+01	-0.91	-0.36
T_{22}	-6.8902E-03	8.2376E-02	8.2664E-02	9.4781E+01	6.49	0.33
T_{33}	-5.7422E-03	8.3113E-02	8.3311E-02	9.3952E+01	7.33	-0.5
T_{44}	-6.8668E-03	8.2363E-02	8.2649E-02	9.4766E+01	6.47	0.31
T_{55}	-2.8487E-03	-1.5203E-02	1.5468E-02	-1.0061E+02	-37.8	-9.19
T_{66}	-2.7899E-03	-1.5159E-02	1.5413E-02	-1.0043E+02	-38	-9.01
T_{77}	-2.4889E-03	-1.5287E-02	1.5489E-02	-9.9247E+01	-37.7	-7.82
T_{88}	-2.7847E-03	-1.5164E-02	1.5418E-02	-1.0041E+02	-38	-8.99
T_{99}	-2.8227E-03	-1.5182E-02	1.5443E-02	-1.0053E+02	-37.9	-9.11

The T-matrix for a spherically symmetric scattered should be diagonal, that is, there should be only one spherical harmonic component of the scattered wave for a single-component incident wave, and it should be the same component as the incident wave. Nonzero off-diagonal components computed for the T-matrix of the spherical elastic shell can be termed

"leakage" (in some abstract sense). The existence of leakage indicates a weakness in the model.

Nonzero off-diagonal components of the T-matrix which were greater than 10^{-14} of the diagonal element were found for a few of the ATILA results. These are given in Table IV below.

TABLE IV. SIGNIFICANT OFF-DIAGONAL T-MATRIX ELEMENTS						
element	real	imag	mag	phase	mag T_{ij} rel to T_{jj}	phase T_{ij} rel to T_{jj}
T_{71}	-7.6679E-04	5.3764E-04	9.3650E-04	1.4496E+02	8.14E-03	48.7
T_{62}	2.2172E-05	7.2191E-06	2.3318E-05	1.8035E+01	2.82E-04	-76.7
T_{84}	-8.9863E-06	-3.8094E-07	8.9944E-06	-1.7757E+02	1.09E-04	-272.3
T_{95}	1.6194E-05	1.4535E-05	2.1761E-05	4.1911E+01	1.41E-03	142.5
T_{28}	-1.1214E-05	4.1657E-08	1.1214E-05	1.7979E+02	7.28E-04	280.2
T_{17}	5.5328E-03	-4.3539E-03	7.0405E-03	-3.8200E+01	4.55E-01	61
T_{48}	3.5575E-05	3.6843E-05	5.1215E-05	4.6003E+01	3.32E-03	146.4
T_{59}	9.8906E-03	7.9364E-03	1.2681E-02	3.8744E+01	8.21E-01	139.3

It is seen that there is significant leakage from the 2,0 to the 0,0 component T_{17}, and from the 2,2 to the 2,-2 component T_{59}, for the finite-element model employed. This could indicate that either the mesh is too coarse, particularly that of the shell, or that the radius of the radiation damping elements which terminate the fluid mesh is too small. These possibilities remain to be investigated.

B. THE ACOUSTIC IMPEDANCE

To further validate the three-dimensional model used in the ATILA code, the acoustic impedance computed analytically and with ATILA output were also compared. The theoretical acoustic impedance, for each harmonic, is given by Equation (42).

On the other hand, output from ATILA can be used to determine the impedance from Equation (41), where F_{nm} will be the total field pressure. Total pressures are output from ATILA when the pressure command in ATILA code (Appendix B) is "PRESSURE TOTAL" [Reference 2]. The terms W_{nm} are also computed from the ATILA output. Averaged values of F_{nm} and W_{nm} were used to compute an approximation to the acoustic impedance of each harmonic. The results are presented in Table VI.

TABLE V. RESULTS OF ACOUSTIC IMPEDANCE		
Theoretical Values	From ATILA	Error and Number of Points
Z_0=0.00-i 0.8396E+07	Z_0=0.5804E+03-i 0.82305E+07	2% and 146
Z_1=0.00+i 0.6945E+06	Z_1=0.26659E+04+i 0.60223E+06	13% and 138

V. CONCLUSIONS

The transition matrix, or "T-matrix", relating the scattered and incident acoustic waves for a thin elastic spherical shell in a free-field environment has been evaluated using the ATILA finite-element code. A three-dimensional finite-element model of a 0.5-m outer radius, 1-cm thick spherical steel shell surrounded by water was developed [Appendix A]. In this model the spherical shell surface is divided into seventy-two approximately equal area triangular regions. The ATILA code was used to calculate the scattered pressure over the surface of the shell for incident waves represented as products of radial Hankel functions and spherical harmonics. This was done for all components through the second order in the Hankel function. The chosen driving frequency was 474 Hz, corresponding to a value of ka=1, where k is the wavenumber of sound in water and a is the radius of the shell. The ATILA results were compared with the results of analytical thin shell theory. For the diagonal elements of the T-matrix , the two results were found to agree within one, seven, and thirty-eight percent, respectively, for the zeroth, first, and second order

components. The ATILA results also produce a few nonzero off-diagonal T-matrix elements which do not appear in the theoretical results, and which should not be present according to symmetry considerations. The reason for the appearance of nonzero off-diagonal elements in the ATILA results is not known at this time and warrants further investigation. Also computed for each harmonic component was the modal acoustical impedance of the shell. These results agreed with the results of thin shell theory within two percent for the zeroth order component and thirteen percent for the first order components.

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APPENDIX A

```
      FUNCTION INCPRE(X,Y,Z,K)
*-----------------------------------------------------------
* PROGRAM BY ARTHUR LOBO DA COSTA RUIZ  12/23/93
*-----------------------------------------------------------
* FUNCTION:
* COMPUTES THE INCIDENT SPHERICAL HARMONIC PRESSURE AT THE POINT
* (X,Y,Z),FOR THE WAVENUMBER K
*
* VARIABLES INPUT:
*           X,Y,Z: CARTESIAN COORDINATES OF THE POINT
*               K: WAVENUMBER
*
* VARIABLES OUTPUT:
*            RADIUS :R IN METERS
*            PHI IN DEGREE (HORIZONTAL ANGLE)
*            THETA IN RADIANS (AZIMUTAL ANGLE)
*            INCPRE : PRESSURE AT POINT IN PASCAL
*-----------------------------------------------------------
     DOUBLE PRECISION K,X,Y,Z,R,PHI,THETA,KR
      REAL*8 PMN(-2:2,0:2),LOUT
      INTEGER N,M,NMAX
      COMPLEX*16 INCPRE,H(0:2),HOUT
*
* N AND M ARE ORDERS FOR HANKEL AND LEGENDRE FUNCTIONS
*
      N=0
      M=0
*
*     HOUT AND LOUT ARE HANKEL AND LEGENDRE OUTPUTS
*     REF TO N AND M
*
      NMAX=2
*
* TRANSFORM CARTESIAN COORDINATES (X,Y,Z)
*        INTO SPHERICAL COORDINATES
* R(RADIUS), PHI(AZIMUTAL ANGLE) AND THETA(POLAR ANGLE)
*
      R=DSQRT(X*X+Y*Y+Z*Z)
      PHI=DATAN2D(Y,X)
      IF((X.EQ.0).AND.(Y.EQ.0)) PHI=0.0D0
      THETA=DACOS(Z/R)
      KR=K*R
*
* NMAX IS THE MAXIMUM NUMBER OF HARMONICS
```

```
*
     CALL HANKEL(KR,NMAX,H)
*
* SUBROUTINE HANKEL RETURNS SPHERICAL HANKEL
*              FUNCTIONS JN AND I YN
*
     CALL LEGNDR(THETA,NMAX,PMN)
     LOUT=PMN(M,N)
*
* SUBROUTINE LEGNDR RETURNS ASSOCIATE LEGENDRE FUNTION
*
     INCPRE=H(N)*LOUT*DCMPLX(DCOSD(M*PHI),DSIND(M*PHI))
     IF ((R.LE.0.501).AND.(R.GT.0.499)) THEN
*    PRINT *,"X,Y,Z =",X,Y,Z
*    PRINT *,"PHI,THETA =",PHI,THETA
*    PRINT *,"K,R,KR =",K,R,KR
*    PRINT *,"REAL HANKEL =",HOUT
*    PRINT *,"LEGENDRE =",LOUT
     PRINT *,INCPRE
*    PRINT *,'****************'
     ELSE
      CONTINUE
     ENDIF
     RETURN
     END
C ****************************************************************
C
     SUBROUTINE HANKEL(X,NMAX,H)
     IMPLICIT REAL*8 (A-H,O-Z)
     COMPLEX*16 H(0:NMAX)
C
C  GIVEN THE VARIABLE X, AND THE MAXIMUM ORDER NMAX,
C    THIS ROUTINE GENERATES THE SPHERICAL HANKEL FUNCTION HN
C    FOR ALL N FROM 0 TO NMAX (INCLUSIVE)
C  INPUT:
C    X = DOUBLE PREC. VARIABLE (RADIUS)
C    NMAX = INTEGER MAXIMUM ORDER OF BESSEL FUNCTIONS DESIRED
C  OUTPUT:
C    H(N) = ARRAY OF SPHERICAL HANKEL FUNCTIONS HN(X), WHERE
C        HN = JN + I YN C C  THIS ROUTINE IS BASED ON THE RECURSION FORMULAE
C    FROM ABRAMOWITZ & STEGUN: 10.1.10 & 10.1.15, PP.438-9
C    THE F' S ARE THE COEFFICIENTS OF ORDER N & -(N+1),
C    THE FO' S ARE OLD F' S, FOR RECURSION
C
     IF ( X .LE. 0.0D0 ) THEN
       H(0) = DCMPLX(1.0D0,-1.0D35)
       DO 2 N = 1, NMAX
          H(N) = CMPLX(0.0D0,-1.0D35)
   2   CONTINUE
       RETURN
     END IF
```

```
      SX = DSIN(X)
      CX = DCOS(X)
      XINV = 1.0D0/X
      M1N = -1.0D0
      FN = XINV
      FMN = 0.0D0
      FNO = FMN
      FMNO = FN
      DO 4 N = 0, NMAX
      H(N) = CMPLX( FN*SX + M1N*FMN*CX, -FN*CX + M1N*FMN*SX )
      T1 = (2*N+1)*XINV
      T2 = T1*FN - FNO
      FNO = FN
      FN = T2
      T2 = -T1*FMN - FMNO
      FMNO = FMN
      FMN = T2
      M1N = -M1N
    4 CONTINUE
      RETURN
      END
C
C *****************************************************************
C
      SUBROUTINE LEGNDR(THETA,NMAX,PMN)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8  PMN(-NMAX:NMAX,0:NMAX)
C
C  GIVEN THE VARIABLE THETA, AND THE MAXIMUM ORDER NMAX,
C    THIS ROUTINE GENERATES THE ASSOC. LEGENDRE FUNCTIONS PMN
C    OF THE ARGUMENT COS(THETA)  (THETA MUST BE BETWEEN 0 & PI)
C    FOR ALL N FROM 0 TO NMAX (INCLUSIVE)
C    AND FOR ALL M FROM -N TO N (SOME OTHERS SET TO ZERO)
C  INPUT:
C    THETA = VARIABLE (POLAR ANGLE), MUST BE BETWEEN 0 & PI (INCL.)
C    NMAX = INTEGER MAXIMUM ORDER OF LEGENDRE FUNCTIONS DESIRED
C  OUTPUT:
C    PMN = DOUBLE PREC. ARRAY, CONTAINS ASSOC. LEGENDRE FNS
C
C  THIS ROUTINE IS BASED ON THE RECURSION FORMULAE
C    FROM ABRAMOWITZ & STEGUN
C
      X = DCOS(THETA)
      SINTHT = DSIN(THETA)
      IF ( SINTHT .GT. 0. ) THEN
       SININV = 1.0D0/SINTHT
      ELSE
       SININV = 0.0D0
      END IF
C  SET VALUES FOR N = 0, 1  (NMAX MUST BE AT LEAST 1)
      PMN(0,0) = 1.0D0
```

```
      PMN(1,0) = 0.0D0
      PMN(-1,0) = 0.0D0
      PMN(0,1) = X
      PMN(1,1) = -SINTHT
      PMN(-1,1) = SINTHT*0.5D0
C  IN LOOP, TNP1 = 2*N+1, TNP2FC = (2*N+2)!, M1N = (-1)**(N+1)
      TNP1 = 1.0D0
      TNP2FC = 2.0D0
      M1N = -1.0D0
      DO 4 N = 1, NMAX-1
        TNP1 = TNP1 + 2.0D0
        TNP2FC = TNP2FC * TNP1 * (TNP1+1)
        M1N = -M1N
        DO 3 M = -N, N
          PMN(M,N+1) = (TNP1*X*PMN(M,N) - (N+M)*PMN(M,N-1))/(N-M+1)
    3   CONTINUE
        PMN(N+1,N) = 0.0D0
        PMN(-N-1,N) = 0.0D0
        PMN(N+1,N+1) = (X*PMN(N,N+1) - TNP1*PMN(N,N)) * SININV
        PMN(-N-1,N+1) = M1N*PMN(N+1,N+1)/TNP2FC
4 CONTINUE
C     DO 120 N=0,NMAX
C     DO 120 M=-N,N
C120  WRITE(6,130) N,M,PMN(M,N)
C130  FORMAT(1X,'  N= ',I4,1X,'  M= ',I4,1X,'  PMN= ',F13.6)
      RETURN
      END
```

APPENDIX B

```
****************************************************
* ATILA MODEL ESHELL4:  3-D ELASTIC SPHERICAL SHELL, 1 CM THICK
* AUTHOR:  BAKER        SHELL RADIUS 0.5 M, MADE OF NEW CURVED SHELL ELEMENTS
*  DATE:  MAR 1994     FLUID RADIUS 2.5 M
*                    EACH OCTANT DIVIDED INTO 9 REGIONS
*                    2 FLUID LAYERS, EACH 0.25 M THICK,
*                    3 FLUID LAYERS, EACH 0.5 M THICK
****************************************************
PRINTING = 2
RADIATION DIPOLAR
ANALYSIS HARMONIC
MATERIAL
 25CD4SH    * PROPERTIES FOR CURVED COMPOSITE SHELL ELEMENTS
0.215E+12  0.330E+00  0.750E+04  0.000E+00  0.000E+00  0.000E+00 &
0.215E+12  0.330E+00  0.750E+04  0.000E+00  1.0        0.000E+00
LCPDDC = 6
NLOAD = 1
FREQUENCY  474.
GEOMETRY
   1
  2.5      * RADIUS OF RADIATION BOUNDARY = 2.5 M
   2
  1  0  0.01    * THICKNESS OF SHELL = 1 CM
PRESSURE SCATTERED
SKYLINE REAL
PRECISION DOUBLE
NEWAXES SPHERICAL
  0  0  0  0  0  0
NODES
* 0001 *  0.490  000  000.0
* 0002 *  0.490  015  000.0
* 0003 *  0.490  015  090.0
* 0004 *  0.490  015  180.0
* 0005 *  0.490  015  270.0
* 0006 *  0.490  030  000.0
* 0007 *  0.490  030  045.0
* 0008 *  0.490  030  090.0
* 0009 *  0.490  030  135.0
* 0010 *  0.490  030  180.0
* 0011 *  0.490  030  225.0
* 0012 *  0.490  030  270.0
* 0013 *  0.490  030  315.0
* 0014 *  0.490  045  000.0
* 0015 *  0.490  045  030.0
```

* 0016 *	0.490	045	060.0
* 0017 *	0.490	045	090.0
* 0018 *	0.490	045	120.0
* 0019 *	0.490	045	150.0
* 0020 *	0.490	045	180.0
* 0021 *	0.490	045	210.0
* 0022 *	0.490	045	240.0
* 0023 *	0.490	045	270.0
* 0024 *	0.490	045	300.0
* 0025 *	0.490	045	330.0
* 0026 *	0.490	060	000.0
* 0027 *	0.490	060	022.5
* 0028 *	0.490	060	045.0
* 0029 *	0.490	060	067.5
* 0030 *	0.490	060	090.0
* 0031 *	0.490	060	112.5
* 0032 *	0.490	060	135.0
* 0033 *	0.490	060	157.5
* 0034 *	0.490	060	180.0
* 0035 *	0.490	060	202.5
* 0036 *	0.490	060	225.0
* 0037 *	0.490	060	247.5
* 0038 *	0.490	060	270.0
* 0039 *	0.490	060	292.5
* 0040 *	0.490	060	315.0
* 0041 *	0.490	060	337.5
* 0042 *	0.490	075	000.0
* 0043 *	0.490	075	018.0
* 0044 *	0.490	075	036.0
* 0045 *	0.490	075	054.0
* 0046 *	0.490	075	072.0
* 0047 *	0.490	075	090.0
* 0048 *	0.490	075	108.0
* 0049 *	0.490	075	126.0
* 0050 *	0.490	075	144.0
* 0051 *	0.490	075	162.0
* 0052 *	0.490	075	180.0
* 0053 *	0.490	075	198.0
* 0054 *	0.490	075	216.0
* 0055 *	0.490	075	234.0
* 0056 *	0.490	075	252.0
* 0057 *	0.490	075	270.0
* 0058 *	0.490	075	288.0
* 0059 *	0.490	075	306.0
* 0060 *	0.490	075	324.0
* 0061 *	0.490	075	342.0
* 0062 *	0.490	090	000.0
* 0063 *	0.490	090	015.0
* 0064 *	0.490	090	030.0
* 0065 *	0.490	090	045.0
* 0066 *	0.490	090	060.0

* 0067 *	0.490	090	075.0
* 0068 *	0.490	090	090.0
* 0069 *	0.490	090	105.0
* 0070 *	0.490	090	120.0
* 0071 *	0.490	090	135.0
* 0072 *	0.490	090	150.0
* 0073 *	0.490	090	165.0
* 0074 *	0.490	090	180.0
* 0075 *	0.490	090	195.0
* 0076 *	0.490	090	210.0
* 0077 *	0.490	090	225.0
* 0078 *	0.490	090	240.0
* 0079 *	0.490	090	255.0
* 0080 *	0.490	090	270.0
* 0081 *	0.490	090	285.0
* 0082 *	0.490	090	300.0
* 0083 *	0.490	090	315.0
* 0084 *	0.490	090	330.0
* 0085 *	0.490	090	345.0
* 0086 *	0.490	105	000.0
* 0087 *	0.490	105	018.0
* 0088 *	0.490	105	036.0
* 0089 *	0.490	105	054.0
* 0090 *	0.490	105	072.0
* 0091 *	0.490	105	090.0
* 0092 *	0.490	105	108.0
* 0093 *	0.490	105	126.0
* 0094 *	0.490	105	144.0
* 0095 *	0.490	105	162.0
* 0096 *	0.490	105	180.0
* 0097 *	0.490	105	198.0
* 0098 *	0.490	105	216.0
* 0099 *	0.490	105	234.0
* 0100 *	0.490	105	252.0
* 0101 *	0.490	105	270.0
* 0102 *	0.490	105	288.0
* 0103 *	0.490	105	306.0
* 0104 *	0.490	105	324.0
* 0105 *	0.490	105	342.0
* 0106 *	0.490	120	000.0
* 0107 *	0.490	120	022.5
* 0108 *	0.490	120	045.0
* 0109 *	0.490	120	067.5
* 0110 *	0.490	120	090.0
* 0111 *	0.490	120	112.5
* 0112 *	0.490	120	135.0
* 0113 *	0.490	120	157.5
* 0114 *	0.490	120	180.0
* 0115 *	0.490	120	202.5
* 0116 *	0.490	120	225.0
* 0117 *	0.490	120	247.5

* 0118 *	0.490	120	270.0
* 0119 *	0.490	120	292.5
* 0120 *	0.490	120	315.0
* 0121 *	0.490	120	337.5
* 0122 *	0.490	135	000.0
* 0123 *	0.490	135	030.0
* 0124 *	0.490	135	060.0
* 0125 *	0.490	135	090.0
* 0126 *	0.490	135	120.0
* 0127 *	0.490	135	150.0
* 0128 *	0.490	135	180.0
* 0129 *	0.490	135	210.0
* 0130 *	0.490	135	240.0
* 0131 *	0.490	135	270.0
* 0132 *	0.490	135	300.0
* 0133 *	0.490	135	330.0
* 0134 *	0.490	150	000.0
* 0135 *	0.490	150	045.0
* 0136 *	0.490	150	090.0
* 0137 *	0.490	150	135.0
* 0138 *	0.490	150	180.0
* 0139 *	0.490	150	225.0
* 0140 *	0.490	150	270.0
* 0141 *	0.490	150	315.0
* 0142 *	0.490	165	000.0
* 0143 *	0.490	165	090.0
* 0144 *	0.490	165	180.0
* 0145 *	0.490	165	270.0
* 0146 *	0.490	180	000.0
* 0147 *	0.000	000	000.0
* 0148 *	0.000	000	000.0
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* 0150 *	0.000	000	000.0
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* 0164 *	0.000	000	000.0
* 0165 *	0.000	000	000.0
* 0166 *	0.000	000	000.0
* 0167 *	0.000	000	000.0
* 0168 *	0.000	000	000.0

*	0169 *	0.000	000	000.0
*	0170 *	0.000	000	000.0
*	0171 *	0.000	000	000.0
*	0172 *	0.000	000	000.0
*	0173 *	0.000	000	000.0
*	0174 *	0.000	000	000.0
*	0175 *	0.000	000	000.0
*	0176 *	0.000	000	000.0
*	0177 *	0.000	000	000.0
*	0178 *	0.000	000	000.0
*	0179 *	0.000	000	000.0
*	0180 *	0.000	000	000.0
*	0181 *	0.000	000	000.0
*	0182 *	0.000	000	000.0
*	0183 *	0.000	000	000.0
*	0184 *	0.000	000	000.0
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*	0186 *	0.000	000	000.0
*	0187 *	0.000	000	000.0
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*	0189 *	0.000	000	000.0
*	0190 *	0.000	000	000.0
*	0191 *	0.000	000	000.0
*	0192 *	0.000	000	000.0
*	0193 *	0.000	000	000.0
*	0194 *	0.000	000	000.0
*	0195 *	0.000	000	000.0
*	0196 *	0.000	000	000.0
*	0197 *	0.000	000	000.0
*	0198 *	0.000	000	000.0
*	0199 *	0.000	000	000.0
*	0200 *	0.000	000	000.0
*	0201 *	0.495	000	000.0
*	0202 *	0.495	015	000.0
*	0203 *	0.495	015	090.0
*	0204 *	0.495	015	180.0
*	0205 *	0.495	015	270.0
*	0206 *	0.495	030	000.0
*	0207 *	0.495	030	045.0
*	0208 *	0.495	030	090.0
*	0209 *	0.495	030	135.0
*	0210 *	0.495	030	180.0
*	0211 *	0.495	030	225.0
*	0212 *	0.495	030	270.0
*	0213 *	0.495	030	315.0
*	0214 *	0.495	045	000.0
*	0215 *	0.495	045	030.0
*	0216 *	0.495	045	060.0
*	0217 *	0.495	045	090.0
*	0218 *	0.495	045	120.0
*	0219 *	0.495	045	150.0

*	0220 *	0.495	045	180.0	
*	0221 *	0.495	045	210.0	
*	0222 *	0.495	045	240.0	
*	0223 *	0.495	045	270.0	
*	0224 *	0.495	045	300.0	
*	0225 *	0.495	045	330.0	
*	0226 *	0.495	060	000.0	
*	0227 *	0.495	060	022.5	
*	0228 *	0.495	060	045.0	
*	0229 *	0.495	060	067.5	
*	0230 *	0.495	060	090.0	
*	0231 *	0.495	060	112.5	
*	0232 *	0.495	060	135.0	
*	0233 *	0.495	060	157.5	
*	0234 *	0.495	060	180.0	
*	0235 *	0.495	060	202.5	
*	0236 *	0.495	060	225.0	
*	0237 *	0.495	060	247.5	
*	0238 *	0.495	060	270.0	
*	0239 *	0.495	060	292.5	
*	0240 *	0.495	060	315.0	
*	0241 *	0.495	060	337.5	
*	0242 *	0.495	075	000.0	
*	0243 *	0.495	075	018.0	
*	0244 *	0.495	075	036.0	
*	0245 *	0.495	075	054.0	
*	0246 *	0.495	075	072.0	
*	0247 *	0.495	075	090.0	
*	0248 *	0.495	075	108.0	
*	0249 *	0.495	075	126.0	
*	0250 *	0.495	075	144.0	
*	0251 *	0.495	075	162.0	
*	0252 *	0.495	075	180.0	
*	0253 *	0.495	075	198.0	
*	0254 *	0.495	075	216.0	
*	0255 *	0.495	075	234.0	
*	0256 *	0.495	075	252.0	
*	0257 *	0.495	075	270.0	
*	0258 *	0.495	075	288.0	
*	0259 *	0.495	075	306.0	
*	0260 *	0.495	075	324.0	
*	0261 *	0.495	075	342.0	
*	0262 *	0.495	090	000.0	
*	0263 *	0.495	090	015.0	
*	0264 *	0.495	090	030.0	
*	0265 *	0.495	090	045.0	
*	0266 *	0.495	090	060.0	
*	0267 *	0.495	090	075.0	
*	0268 *	0.495	090	090.0	
*	0269 *	0.495	090	105.0	
*	0270 *	0.495	090	120.0	

*	0271 *	0.495	090	135.0
*	0272 *	0.495	090	150.0
*	0273 *	0.495	090	165.0
*	0274 *	0.495	090	180.0
*	0275 *	0.495	090	195.0
*	0276 *	0.495	090	210.0
*	0277 *	0.495	090	225.0
*	0278 *	0.495	090	240.0
*	0279 *	0.495	090	255.0
*	0280 *	0.495	090	270.0
*	0281 *	0.495	090	285.0
*	0282 *	0.495	090	300.0
*	0283 *	0.495	090	315.0
*	0284 *	0.495	090	330.0
*	0285 *	0.495	090	345.0
*	0286 *	0.495	105	000.0
*	0287 *	0.495	105	018.0
*	0288 *	0.495	105	036.0
*	0289 *	0.495	105	054.0
*	0290 *	0.495	105	072.0
*	0291 *	0.495	105	090.0
*	0292 *	0.495	105	108.0
*	0293 *	0.495	105	126.0
*	0294 *	0.495	105	144.0
*	0295 *	0.495	105	162.0
*	0296 *	0.495	105	180.0
*	0297 *	0.495	105	198.0
*	0298 *	0.495	105	216.0
*	0299 *	0.495	105	234.0
*	0300 *	0.495	105	252.0
*	0301 *	0.495	105	270.0
*	0302 *	0.495	105	288.0
*	0303 *	0.495	105	306.0
*	0304 *	0.495	105	324.0
*	0305 *	0.495	105	342.0
*	0306 *	0.495	120	000.0
*	0307 *	0.495	120	022.5
*	0308 *	0.495	120	045.0
*	0309 *	0.495	120	067.5
*	0310 *	0.495	120	090.0
*	0311 *	0.495	120	112.5
*	0312 *	0.495	120	135.0
*	0313 *	0.495	120	157.5
*	0314 *	0.495	120	180.0
*	0315 *	0.495	120	202.5
*	0316 *	0.495	120	225.0
*	0317 *	0.495	120	247.5
*	0318 *	0.495	120	270.0
*	0319 *	0.495	120	292.5
*	0320 *	0.495	120	315.0
*	0321 *	0.495	120	337.5

*	0322 *	0.495	135	000.0
*	0323 *	0.495	135	030.0
*	0324 *	0.495	135	060.0
*	0325 *	0.495	135	090.0
*	0326 *	0.495	135	120.0
*	0327 *	0.495	135	150.0
*	0328 *	0.495	135	180.0
*	0329 *	0.495	135	210.0
*	0330 *	0.495	135	240.0
*	0331 *	0.495	135	270.0
*	0332 *	0.495	135	300.0
*	0333 *	0.495	135	330.0
*	0334 *	0.495	150	000.0
*	0335 *	0.495	150	045.0
*	0336 *	0.495	150	090.0
*	0337 *	0.495	150	135.0
*	0338 *	0.495	150	180.0
*	0339 *	0.495	150	225.0
*	0340 *	0.495	150	270.0
*	0341 *	0.495	150	315.0
*	0342 *	0.495	165	000.0
*	0343 *	0.495	165	090.0
*	0344 *	0.495	165	180.0
*	0345 *	0.495	165	270.0
*	0346 *	0.495	180	000.0
*	0347 *	0.000	000	000.0
*	0348 *	0.000	000	000.0
*	0349 *	0.000	000	000.0
*	0350 *	0.000	000	000.0
*	0351 *	0.000	000	000.0
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*	0353 *	0.000	000	000.0
*	0354 *	0.000	000	000.0
*	0355 *	0.000	000	000.0
*	0356 *	0.000	000	000.0
*	0357 *	0.000	000	000.0
*	0358 *	0.000	000	000.0
*	0359 *	0.000	000	000.0
*	0360 *	0.000	000	000.0
*	0361 *	0.000	000	000.0
*	0362 *	0.000	000	000.0
*	0363 *	0.000	000	000.0
*	0364 *	0.000	000	000.0
*	0365 *	0.000	000	000.0
*	0366 *	0.000	000	000.0
*	0367 *	0.000	000	000.0
*	0368 *	0.000	000	000.0
*	0369 *	0.000	000	000.0
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* 0861 *	0.625	075	342.0
* 0862 *	0.625	090	000.0
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* 0864 *	0.625	090	030.0
* 0865 *	0.625	090	045.0
* 0866 *	0.625	090	060.0
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* 0869 *	0.625	090	105.0
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* 0871 *	0.625	090	135.0
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* 0874 *	0.625	090	180.0
* 0875 *	0.625	090	195.0
* 0876 *	0.625	090	210.0
* 0877 *	0.625	090	225.0
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* 0880 *	0.625	090	270.0
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* 0882 *	0.625	090	300.0

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*	0890 *	0.625	105	072.0
*	0891 *	0.625	105	090.0
*	0892 *	0.625	105	108.0
*	0893 *	0.625	105	126.0
*	0894 *	0.625	105	144.0
*	0895 *	0.625	105	162.0
*	0896 *	0.625	105	180.0
*	0897 *	0.625	105	198.0
*	0898 *	0.625	105	216.0
*	0899 *	0.625	105	234.0
*	0900 *	0.625	105	252.0
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*	0903 *	0.625	105	306.0
*	0904 *	0.625	105	324.0
*	0905 *	0.625	105	342.0
*	0906 *	0.625	120	000.0
*	0907 *	0.625	120	022.5
*	0908 *	0.625	120	045.0
*	0909 *	0.625	120	067.5
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*	0913 *	0.625	120	157.5
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*	0917 *	0.625	120	247.5
*	0918 *	0.625	120	270.0
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*	0923 *	0.625	135	030.0
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*	0933 *	0.625	135	330.0

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* 0940 *	0.625	150	270.0
* 0941 *	0.625	150	315.0
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*	1001 *	0.750	000	000.0
*	1002 *	0.750	015	000.0
*	1003 *	0.750	015	090.0
*	1004 *	0.750	015	180.0
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*	1007 *	0.750	030	045.0
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*	1024 *	0.750	045	300.0
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*	1031 *	0.750	060	112.5
*	1032 *	0.750	060	135.0
*	1033 *	0.750	060	157.5
*	1034 *	0.750	060	180.0
*	1035 *	0.750	060	202.5

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* 1037 *	0.750	060	247.5
* 1038 *	0.750	060	270.0
* 1039 *	0.750	060	292.5
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* 1050 *	0.750	075	144.0
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* 1053 *	0.750	075	198.0
* 1054 *	0.750	075	216.0
* 1055 *	0.750	075	234.0
* 1056 *	0.750	075	252.0
* 1057 *	0.750	075	270.0
* 1058 *	0.750	075	288.0
* 1059 *	0.750	075	306.0
* 1060 *	0.750	075	324.0
* 1061 *	0.750	075	342.0
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* 1083 *	0.750	090	315.0
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* 1237 *	0.875	060	247.5
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* 1239 *	0.875	060	292.5

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*	1333 *	0.875	135	330.0
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*	1337 *	0.875	150	135.0
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*	1341 *	0.875	150	315.0

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* 1343 *	0.875	165	090.0
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* 1345 *	0.875	165	270.0
* 1346 *	0.875	180	000.0
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* 1853 *	1.500	075	198.0
* 1854 *	1.500	075	216.0
* 1855 *	1.500	075	234.0
* 1856 *	1.500	075	252.0
* 1857 *	1.500	075	270.0
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* 1859 *	1.500	075	306.0
* 1860 *	1.500	075	324.0
* 1861 *	1.500	075	342.0
* 1862 *	1.500	090	000.0
* 1863 *	1.500	090	015.0
* 1864 *	1.500	090	030.0
* 1865 *	1.500	090	045.0
* 1866 *	1.500	090	060.0
* 1867 *	1.500	090	075.0
* 1868 *	1.500	090	090.0
* 1869 *	1.500	090	105.0
* 1870 *	1.500	090	120.0
* 1871 *	1.500	090	135.0
* 1872 *	1.500	090	150.0
* 1873 *	1.500	090	165.0
* 1874 *	1.500	090	180.0
* 1875 *	1.500	090	195.0
* 1876 *	1.500	090	210.0
* 1877 *	1.500	090	225.0
* 1878 *	1.500	090	240.0
* 1879 *	1.500	090	255.0
* 1880 *	1.500	090	270.0
* 1881 *	1.500	090	285.0
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* 1888 *	1.500	105	036.0
* 1889 *	1.500	105	054.0
* 1890 *	1.500	105	072.0
* 1891 *	1.500	105	090.0
* 1892 *	1.500	105	108.0
* 1893 *	1.500	105	126.0
* 1894 *	1.500	105	144.0
* 1895 *	1.500	105	162.0
* 1896 *	1.500	105	180.0
* 1897 *	1.500	105	198.0
* 1898 *	1.500	105	216.0
* 1899 *	1.500	105	234.0
* 1900 *	1.500	105	252.0
* 1901 *	1.500	105	270.0
* 1902 *	1.500	105	288.0

*	1903 *	1.500	105	306.0
*	1904 *	1.500	105	324.0
*	1905 *	1.500	105	342.0
*	1906 *	1.500	120	000.0
*	1907 *	1.500	120	022.5
*	1908 *	1.500	120	045.0
*	1909 *	1.500	120	067.5
*	1910 *	1.500	120	090.0
*	1911 *	1.500	120	112.5
*	1912 *	1.500	120	135.0
*	1913 *	1.500	120	157.5
*	1914 *	1.500	120	180.0
*	1915 *	1.500	120	202.5
*	1916 *	1.500	120	225.0
*	1917 *	1.500	120	247.5
*	1918 *	1.500	120	270.0
*	1919 *	1.500	120	292.5
*	1920 *	1.500	120	315.0
*	1921 *	1.500	120	337.5
*	1922 *	1.500	135	000.0
*	1923 *	1.500	135	030.0
*	1924 *	1.500	135	060.0
*	1925 *	1.500	135	090.0
*	1926 *	1.500	135	120.0
*	1927 *	1.500	135	150.0
*	1928 *	1.500	135	180.0
*	1929 *	1.500	135	210.0
*	1930 *	1.500	135	240.0
*	1931 *	1.500	135	270.0
*	1932 *	1.500	135	300.0
*	1933 *	1.500	135	330.0
*	1934 *	1.500	150	000.0
*	1935 *	1.500	150	045.0
*	1936 *	1.500	150	090.0
*	1937 *	1.500	150	135.0
*	1938 *	1.500	150	180.0
*	1939 *	1.500	150	225.0
*	1940 *	1.500	150	270.0
*	1941 *	1.500	150	315.0
*	1942 *	1.500	165	000.0
*	1943 *	1.500	165	090.0
*	1944 *	1.500	165	180.0
*	1945 *	1.500	165	270.0
*	1946 *	1.500	180	000.0
*	1947 *	0.000	000	000.0
*	1948 *	0.000	000	000.0
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*	1950 *	0.000	000	000.0
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*	1953 *	0.000	000	000.0

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* 1989 *	0.000	000	000.0
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* 1992 *	0.000	000	000.0
* 1993 *	0.000	000	000.0
* 1994 *	0.000	000	000.0
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* 1996 *	0.000	000	000.0
* 1997 *	0.000	000	000.0
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* 2000 *	0.000	000	000.0
* 2001 *	1.750	000	000.0
* 2002 *	1.750	015	000.0
* 2003 *	1.750	015	090.0
* 2004 *	1.750	015	180.0

* 2005 *	1.750	015	270.0
* 2006 *	1.750	030	000.0
* 2007 *	1.750	030	045.0
* 2008 *	1.750	030	090.0
* 2009 *	1.750	030	135.0
* 2010 *	1.750	030	180.0
* 2011 *	1.750	030	225.0
* 2012 *	1.750	030	270.0
* 2013 *	1.750	030	315.0
* 2014 *	1.750	045	000.0
* 2015 *	1.750	045	030.0
* 2016 *	1.750	045	060.0
* 2017 *	1.750	045	090.0
* 2018 *	1.750	045	120.0
* 2019 *	1.750	045	150.0
* 2020 *	1.750	045	180.0
* 2021 *	1.750	045	210.0
* 2022 *	1.750	045	240.0
* 2023 *	1.750	045	270.0
* 2024 *	1.750	045	300.0
* 2025 *	1.750	045	330.0
* 2026 *	1.750	060	000.0
* 2027 *	1.750	060	022.5
* 2028 *	1.750	060	045.0
* 2029 *	1.750	060	067.5
* 2030 *	1.750	060	090.0
* 2031 *	1.750	060	112.5
* 2032 *	1.750	060	135.0
* 2033 *	1.750	060	157.5
* 2034 *	1.750	060	180.0
* 2035 *	1.750	060	202.5
* 2036 *	1.750	060	225.0
* 2037 *	1.750	060	247.5
* 2038 *	1.750	060	270.0
* 2039 *	1.750	060	292.5
* 2040 *	1.750	060	315.0
* 2041 *	1.750	060	337.5
* 2042 *	1.750	075	000.0
* 2043 *	1.750	075	018.0
* 2044 *	1.750	075	036.0
* 2045 *	1.750	075	054.0
* 2046 *	1.750	075	072.0
* 2047 *	1.750	075	090.0
* 2048 *	1.750	075	108.0
* 2049 *	1.750	075	126.0
* 2050 *	1.750	075	144.0
* 2051 *	1.750	075	162.0
* 2052 *	1.750	075	180.0
* 2053 *	1.750	075	198.0
* 2054 *	1.750	075	216.0
* 2055 *	1.750	075	234.0

*	2056 *	1.750	075	252.0	
*	2057 *	1.750	075	270.0	
*	2058 *	1.750	075	288.0	
*	2059 *	1.750	075	306.0	
*	2060 *	1.750	075	324.0	
*	2061 *	1.750	075	342.0	
*	2062 *	1.750	090	000.0	
*	2063 *	1.750	090	015.0	
*	2064 *	1.750	090	030.0	
*	2065 *	1.750	090	045.0	
*	2066 *	1.750	090	060.0	
*	2067 *	1.750	090	075.0	
*	2068 *	1.750	090	090.0	
*	2069 *	1.750	090	105.0	
*	2070 *	1.750	090	120.0	
*	2071 *	1.750	090	135.0	
*	2072 *	1.750	090	150.0	
*	2073 *	1.750	090	165.0	
*	2074 *	1.750	090	180.0	
*	2075 *	1.750	090	195.0	
*	2076 *	1.750	090	210.0	
*	2077 *	1.750	090	225.0	
*	2078 *	1.750	090	240.0	
*	2079 *	1.750	090	255.0	
*	2080 *	1.750	090	270.0	
*	2081 *	1.750	090	285.0	
*	2082 *	1.750	090	300.0	
*	2083 *	1.750	090	315.0	
*	2084 *	1.750	090	330.0	
*	2085 *	1.750	090	345.0	
*	2086 *	1.750	105	000.0	
*	2087 *	1.750	105	018.0	
*	2088 *	1.750	105	036.0	
*	2089 *	1.750	105	054.0	
*	2090 *	1.750	105	072.0	
*	2091 *	1.750	105	090.0	
*	2092 *	1.750	105	108.0	
*	2093 *	1.750	105	126.0	
*	2094 *	1.750	105	144.0	
*	2095 *	1.750	105	162.0	
*	2096 *	1.750	105	180.0	
*	2097 *	1.750	105	198.0	
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*	2110 *	1.750	120	090.0
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*	2112 *	1.750	120	135.0
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*	2114 *	1.750	120	180.0
*	2115 *	1.750	120	202.5
*	2116 *	1.750	120	225.0
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*	2118 *	1.750	120	270.0
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*	2120 *	1.750	120	315.0
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*	2122 *	1.750	135	000.0
*	2123 *	1.750	135	030.0
*	2124 *	1.750	135	060.0
*	2125 *	1.750	135	090.0
*	2126 *	1.750	135	120.0
*	2127 *	1.750	135	150.0
*	2128 *	1.750	135	180.0
*	2129 *	1.750	135	210.0
*	2130 *	1.750	135	240.0
*	2131 *	1.750	135	270.0
*	2132 *	1.750	135	300.0
*	2133 *	1.750	135	330.0
*	2134 *	1.750	150	000.0
*	2135 *	1.750	150	045.0
*	2136 *	1.750	150	090.0
*	2137 *	1.750	150	135.0
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*	2139 *	1.750	150	225.0
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*	2144 *	1.750	165	180.0
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* 2192 *	0.000	000	000.0
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* 2201 *	2.000	000	000.0
* 2202 *	2.000	015	000.0
* 2203 *	2.000	015	090.0
* 2204 *	2.000	015	180.0
* 2205 *	2.000	015	270.0
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* 2207 *	2.000	030	045.0
* 2208 *	2.000	030	090.0

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*	2211 *	2.000	030	225.0
*	2212 *	2.000	030	270.0
*	2213 *	2.000	030	315.0
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*	2215 *	2.000	045	030.0
*	2216 *	2.000	045	060.0
*	2217 *	2.000	045	090.0
*	2218 *	2.000	045	120.0
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*	2220 *	2.000	045	180.0
*	2221 *	2.000	045	210.0
*	2222 *	2.000	045	240.0
*	2223 *	2.000	045	270.0
*	2224 *	2.000	045	300.0
*	2225 *	2.000	045	330.0
*	2226 *	2.000	060	000.0
*	2227 *	2.000	060	022.5
*	2228 *	2.000	060	045.0
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*	2230 *	2.000	060	090.0
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*	2232 *	2.000	060	135.0
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*	2235 *	2.000	060	202.5
*	2236 *	2.000	060	225.0
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*	2238 *	2.000	060	270.0
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*	2240 *	2.000	060	315.0
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*	2244 *	2.000	075	036.0
*	2245 *	2.000	075	054.0
*	2246 *	2.000	075	072.0
*	2247 *	2.000	075	090.0
*	2248 *	2.000	075	108.0
*	2249 *	2.000	075	126.0
*	2250 *	2.000	075	144.0
*	2251 *	2.000	075	162.0
*	2252 *	2.000	075	180.0
*	2253 *	2.000	075	198.0
*	2254 *	2.000	075	216.0
*	2255 *	2.000	075	234.0
*	2256 *	2.000	075	252.0
*	2257 *	2.000	075	270.0
*	2258 *	2.000	075	288.0
*	2259 *	2.000	075	306.0

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* 2261 *	2.000	075	342.0
* 2262 *	2.000	090	000.0
* 2263 *	2.000	090	015.0
* 2264 *	2.000	090	030.0
* 2265 *	2.000	090	045.0
* 2266 *	2.000	090	060.0
* 2267 *	2.000	090	075.0
* 2268 *	2.000	090	090.0
* 2269 *	2.000	090	105.0
* 2270 *	2.000	090	120.0
* 2271 *	2.000	090	135.0
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* 2273 *	2.000	090	165.0
* 2274 *	2.000	090	180.0
* 2275 *	2.000	090	195.0
* 2276 *	2.000	090	210.0
* 2277 *	2.000	090	225.0
* 2278 *	2.000	090	240.0
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* 2281 *	2.000	090	285.0
* 2282 *	2.000	090	300.0
* 2283 *	2.000	090	315.0
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* 2286 *	2.000	105	000.0
* 2287 *	2.000	105	018.0
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* 2289 *	2.000	105	054.0
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* 2291 *	2.000	105	090.0
* 2292 *	2.000	105	108.0
* 2293 *	2.000	105	126.0
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* 2297 *	2.000	105	198.0
* 2298 *	2.000	105	216.0
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* 2300 *	2.000	105	252.0
* 2301 *	2.000	105	270.0
* 2302 *	2.000	105	288.0
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* 2305 *	2.000	105	342.0
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* 2308 *	2.000	120	045.0
* 2309 *	2.000	120	067.5
* 2310 *	2.000	120	090.0

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*	2312 *	2.000	120	135.0
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*	2314 *	2.000	120	180.0
*	2315 *	2.000	120	202.5
*	2316 *	2.000	120	225.0
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*	2318 *	2.000	120	270.0
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*	2320 *	2.000	120	315.0
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*	2322 *	2.000	135	000.0
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*	2324 *	2.000	135	060.0
*	2325 *	2.000	135	090.0
*	2326 *	2.000	135	120.0
*	2327 *	2.000	135	150.0
*	2328 *	2.000	135	180.0
*	2329 *	2.000	135	210.0
*	2330 *	2.000	135	240.0
*	2331 *	2.000	135	270.0
*	2332 *	2.000	135	300.0
*	2333 *	2.000	135	330.0
*	2334 *	2.000	150	000.0
*	2335 *	2.000	150	045.0
*	2336 *	2.000	150	090.0
*	2337 *	2.000	150	135.0
*	2338 *	2.000	150	180.0
*	2339 *	2.000	150	225.0
*	2340 *	2.000	150	270.0
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*	2342 *	2.000	165	000.0
*	2343 *	2.000	165	090.0
*	2344 *	2.000	165	180.0
*	2345 *	2.000	165	270.0
*	2346 *	2.000	180	000.0
*	2347 *	0.000	000	000.0
*	2348 *	0.000	000	000.0
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2628 2664 2666 2644 2665 2645
2666 2630 2628 2646 2629 2645
2630 2666 2668 2646 2667 2647

2630	2668	2670	2647	2669	2648
2670	2632	2630	2649	2631	2648
2632	2670	2672	2649	2671	2650
2672	2634	2632	2651	2633	2650
2634	2672	2674	2651	2673	2652
2634	2674	2676	2652	2675	2653
2676	2636	2634	2654	2635	2653
2636	2676	2678	2654	2677	2655
2678	2638	2636	2656	2637	2655
2638	2678	2680	2656	2679	2657
2638	2680	2682	2657	2681	2658
2682	2640	2638	2659	2639	2658
2640	2682	2684	2659	2683	2660
2684	2626	2640	2661	2641	2660
2626	2684	2662	2661	2685	2642
2706	2664	2662	2687	2663	2686
2664	2706	2708	2687	2707	2688
2708	2666	2664	2689	2665	2688
2666	2708	2710	2689	2709	2690
2710	2668	2666	2691	2667	2690
2710	2670	2668	2692	2669	2691
2670	2710	2712	2692	2711	2693
2712	2672	2670	2694	2671	2693
2672	2712	2714	2694	2713	2695
2714	2674	2672	2696	2673	2695
2714	2676	2674	2697	2675	2696
2676	2714	2716	2697	2715	2698
2716	2678	2676	2699	2677	2698
2678	2716	2718	2699	2717	2700
2718	2680	2678	2701	2679	2700
2718	2682	2680	2702	2681	2701
2682	2718	2720	2702	2719	2703
2720	2684	2682	2704	2683	2703
2684	2720	2706	2704	2721	2705
2706	2662	2684	2686	2685	2705
2734	2708	2706	2723	2707	2722
2708	2734	2736	2723	2735	2724
2736	2710	2708	2725	2709	2724
2736	2712	2710	2726	2711	2725
2712	2736	2738	2726	2737	2727
2738	2714	2712	2728	2713	2727
2738	2716	2714	2729	2715	2728
2716	2738	2740	2729	2739	2730
2740	2718	2716	2731	2717	2730
2740	2720	2718	2732	2719	2731
2720	2740	2734	2732	2741	2733
2734	2706	2720	2722	2721	2733
2746	2736	2734	2743	2735	2742
2746	2738	2736	2744	2737	2743
2746	2740	2738	2745	2739	2744
2746	2734	2740	2742	2741	2745

END

APPENDIX C.

```
      PROGRAM BNDMAT
      CALL SVDSUB
      STOP
      END
C
C ***************************************************************
C
      SUBROUTINE SVDSUB
C ***********************************************************
      PARAMETER (NHARM=2,MSPHER=3,
     1 IBLOCK=(NHARM+1)**2,NPOINT=146)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMPLEX*16 CZERO,CONE,CI,HRADB(0:NHARM),MATINF(NPOINT,IBLOCK),
     1 WK(NPOINT),SIG(IBLOCK),EXTRA(IBLOCK),VM(IBLOCK,IBLOCK),
     2 UM(NPOINT,NPOINT),UIINV(IBLOCK,NPOINT),PHIFAC,PDATA(NPOINT),
     3 ACHK(IBLOCK),RES(NPOINT),MATCHK(NPOINT,IBLOCK),HRADR(0:NHARM),
     4 CTEM1,ZZCHK
      REAL*8 KK,KA,PMX(-NHARM:NHARM,0:NHARM),KR
      COMMON/COM0/CZERO,CONE,CI,ORIGIN(0:MSPHER,3)
C ***********************************************************
      PI=4.0D0*DATAN(1.0D0)
C
C THIS ROUTINE INITIALIZES ARRAYS FOR THE MAIN ROUTINE
C   SPECIFICALLY, IT:
C     SETS COMPLEX CONSTANTS FOR 0, 1, AND I
C     COMPUTES HANKEL & BESSEL FUNCTIONS (& DERIVATIVES) FOR RADIUS
C
C INPUT:
C    KK = WAVENUMBER
C    RADSPH = RADIUS OF SPHERE
C    CFLD=FLUID WAVE SPEED  1524 METERS/SEC
C    FLDDEN=FLUID DENSITY 1000 KG/METER**3
C    RHOC = RHO*C, RADIATION IMPEDANCE OF MEDIUM
C    X,Y,Z = COORDINATES FOR EACH SPHERE
C    NPOINT = NUMBER OF DATA POINTS USED IN THE CALCULATION
C
C SET COMPLEX CONSTANTS
      CZERO = DCMPLX(0.0D0,0.0D0)
      CONE  = DCMPLX(1.0D0,0.0D0)
      CI    = DCMPLX(0.0D0,1.0D0)
C  INPUT THE EXCITATION MODE MMI AND NNI
      MMI=0
      NNI=2
      III=NNI*NNI+NNI+MMI+1
```

```
C  INPUT WAVENUMBER, SPHERE RADIUS, AND MEDIUM' S DENSITY*SOUND SPEED
      RADSPH=0.5D0
      CFLD=1492.94D0
      HERTZ=474.0D0
      KK = 2*PI*HERTZ/CFLD
      FLDDEN=1000.0D0
      RHOC=CFLD*FLDDEN
      KA = KK*RADSPH
      WRITE(6,21) KK,RADSPH,RHOC
 21   FORMAT(5X,' K= ' ,1E10.4,'  A= ' ,E10.4,'   RHO*C =' ,E10.4)
      CALL HANKEL(KA,NHARM,HRADB)
*********************
C THE DATA FILE MUST RESIDE IN UNIT 12 TO DO THE FOLLOWING
      DO 10 I=1,NPOINT
      READ(12,15) X,Y,Z,PDATA(I)
 15   FORMAT(E11.3,E12.3,E12.3,E13.3,E12.3)
      IF(I.EQ.1) THEN
         RBND=DSQRT(X**2+Y**2+Z**2)
         KR=KK*RBND
          PRINT *,KR
         CALL HANKEL(KR,NHARM,HRADR)
      ENDIF
      THETX=DATAN2(DSQRT(X**2+Y**2),Z)
      CALL LEGNDR(THETX,NHARM,PMX)
      PHIX=DATAN2(Y,X)
C  THE FOLLOWING IS TO CHECK  OUTPUTS FROM ATILA N=1, M=-1
C
C     ZZCHK=DCMPLX( 0.97307D0, 0.23051D0)*DCONJG(HRADR(0))
C     ZZCHK=DCMPLX(0.98795D0, 0.15478D0)*DCONJG(HRADR(NNI))*
C    1  PMX(MMI,NNI)*DCMPLX(DCOS(MMI*PHIX),DSIN(MMI*PHIX))
      ZZCHK=DCMPLX(0.99876D0,-0.049693D0)*DCONJG(HRADR(NNI))*
     1  PMX(MMI,NNI)*DCMPLX(DCOS(MMI*PHIX),DSIN(MMI*PHIX))
C
C
C     PDATA(I)=ZZCHK
      PHASED=DATAN2(DIMAG(PDATA(I)),DREAL(PDATA(I)))
      PHASEA=DATAN2(DIMAG(ZZCHK),DREAL(ZZCHK))
C
      WRITE(6,16) X,Y,Z,PDATA(I),CDABS(PDATA(I)),
     1 ZZCHK,CDABS(ZZCHK)
      ZZCHK=ZZCHK-PDATA(I)
      WRITE(6,617) ZZCHK,CDABS(ZZCHK)
617   FORMAT(13X,2E17.5,E17.5)
      WRITE(6,616) PHASED,PHASEA,PHASEA-PHASED
616   FORMAT(7X,3E17.6)
 16   FORMAT(2X,6E12.3,/,38X,3E12.3)
      WRITE(25,125) PHIX,PHASED
 125  FORMAT(2X,2F13.5)
      DO 10 N=0,NHARM
      DO 10 M=-N,N
      PHIFAC=DCMPLX(DCOS(M*PHIX),DSIN(M*PHIX))
```

```
      JJ=N*N+N+M+1
      MATINF(I,JJ)=DCONJG(HRADR(N))*PMX(M,N)*PHIFAC
      MATCHK(I,JJ)=MATINF(I,JJ)
   10 CONTINUE
      CALL ZSVDC(MATINF,NPOINT,NPOINT,IBLOCK,SIG,EXTRA,UM,NPOINT,VM,
     1 IBLOCK,WK,21,INFOX)
      WRITE(6,30) (SIG(I),I=1,IBLOCK)
   30 FORMAT(1X,2E20.5)
      DO 40 I=1,IBLOCK
      DO 40 J=1,NPOINT
      UIINV(I,J)=CZERO
      DO 40 K=1,IBLOCK
      IF(CDABS(SIG(K)).LT.10E-8) GO TO 40
      UIINV(I,J)=UIINV(I,J)+VM(I,K)*DCONJG(UM(J,K))/SIG(K)
   40 CONTINUE
      DO 50 I=1,IBLOCK
      ACHK(I)=CZERO
      DO 50 K=1,NPOINT
      ACHK(I)=ACHK(I)+UIINV(I,K)*PDATA(K)
   50 CONTINUE
      WRITE(6,160)
  160 FORMAT(1X,' THE FOLLOWING ARE THE UNMODIFIED T MATRIX ELEMENTS' ,/,
     1 1X,' OR THE VALUES OF THE RADIATED PRESSURES' )
      DO 55 N=0,NHARM
      DO 55 M=-N,N
      I=N*N+N+M+1
      CTEM1=ACHK(I)
   55 WRITE(6,60) I,CTEM1,CDABS(CTEM1)
   60 FORMAT(1X,I3,1X,3E20.5)
      WRITE(6,161)
  161 FORMAT(1X,' THE FOLLOWING ARE THE TRUE T MATRIX ELEMENTS' )
C III IS THE EXCITATION MODE EG FOR M=0,N=0 III=1
      DO 155 N=0,NHARM
      DO 155 M=-N,N
      I=N*N+N+M+1
      IF((N.EQ.NNI).AND.(M.EQ.MMI)) THEN
        CTEM1=0.5D0*(ACHK(I)-1.0D0)
      ELSE
        CTEM1=ACHK(I)
      ENDIF
  155 WRITE(6,60) I,CTEM1,CDABS(CTEM1)
C WANT TO GET A HANDLE ON THE RELATIVE ERROR INVOLVED IN THE SVD CALC
      DO 70 J=1,NPOINT
      RES(J)=DCMPLX(0.0D0,0.0D0)
      DO 80 I=1,IBLOCK  80 RES(J)=RES(J)+MATCHK(J,I)*ACHK(I)
      RES(J)=RES(J)-PDATA(J)
   70 CONTINUE
      DO 100 I=1,NPOINT
      RESM=RESM+RES(I)*DCONJG(RES(I))
      DATAM=DATAM+PDATA(I)*CONJG(PDATA(I))
  100 CONTINUE
```

```
      RELERR=RESM/DATAM
      WRITE(6,110) RESM,DATAM,RELERR
110   FORMAT(1X,' MAGNITUDE OF RESIDUAL = ' , E15.6,/,1X,
     1       ' MAGNITUDE OF DATA = ' , E15.6,/,1X,
     2       ' RELATIVE ERROR IN THE CALCULATION = ' , E15.6)
      RETURN
      END
C
C ************************************************************
C
      SUBROUTINE HANKEL(X,NMAX,H)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMPLEX*16 H(0:NMAX)
C
C  GIVEN THE VARIABLE X, AND THE MAXIMUM ORDER NMAX,
C    THIS ROUTINE GENERATES THE SPHERICAL HANKEL FUNCTION HN
C    FOR ALL N FROM 0 TO NMAX (INCLUSIVE)
C  INPUT:
C    X = DOUBLE PREC. VARIABLE (RADIUS)
C    NMAX = INTEGER MAXIMUM ORDER OF BESSEL FUNCTIONS DESIRED
C  OUTPUT:
C    H(N) = ARRAY OF SPHERICAL HANKEL FUNCTIONS HN(X), WHERE
C         HN = JN + I YN
C
C  THIS ROUTINE IS BASED ON THE RECURSION FORMULAE
C    FROM ABRAMOWITZ & STEGUN: 10.1.10 & 10.1.15, PP.438-9
C    THE F' S ARE THE COEFFICIENTS OF ORDER N & -(N+1),
C    THE FO' S ARE OLD F' S, FOR RECURSION
C
      IF ( X .LE. 0.0D0 ) THEN
        H(0) = DCMPLX(1.0D0,-1.0D35)
        DO 2 N = 1, NMAX
          H(N) = CMPLX(0.0D0,-1.0D35)
  2     CONTINUE
        RETURN
      END IF
      SX = DSIN(X)
      CX = DCOS(X)
      XINV = 1.0D0/X
      M1N = -1.0D0
      FN = XINV
      FMN = 0.0D0
      FNO = FMN
      FMNO = FN
      DO 4 N = 0, NMAX
      H(N) = CMPLX( FN*SX + M1N*FMN*CX, -FN*CX + M1N*FMN*SX )
      T1 = (2*N+1)*XINV
      T2 = T1*FN - FNO
      FNO = FN
      FN = T2
      T2 = -T1*FMN - FMNO
```

```
      FMNO = FMN
      FMN = T2
      M1N = -M1N
    4 CONTINUE
      RETURN
      END
C
C ***********************************************************************
C
      SUBROUTINE LEGNDR(THETA,NMAX,PMN)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8  PMN(-NMAX:NMAX,0:NMAX)
C
C  GIVEN THE VARIABLE THETA, AND THE MAXIMUM ORDER NMAX,
C    THIS ROUTINE GENERATES THE ASSOC. LEGENDRE FUNCTIONS PMN
C    OF THE ARGUMENT COS(THETA)  (THETA MUST BE BETWEEN 0 & PI)
C    FOR ALL N FROM 0 TO NMAX (INCLUSIVE)
C    AND FOR ALL M FROM -N TO N (SOME OTHERS SET TO ZERO)
C  INPUT:
C    THETA = VARIABLE (POLAR ANGLE), MUST BE BETWEEN 0 & PI (INCL.)
C    NMAX = INTEGER MAXIMUM ORDER OF LEGENDRE FUNCTIONS DESIRED
C  OUTPUT:
C    PMN = DOUBLE PREC. ARRAY, CONTAINS ASSOC. LEGENDRE FNS
C
C  THIS ROUTINE IS BASED ON THE RECURSION FORMULAE
C    FROM ABRAMOWITZ & STEGUN
C
      X = DCOS(THETA)
      SINTHT = DSIN(THETA)
      IF ( SINTHT .GT. 0. ) THEN
       SININV = 1.0D0/SINTHT
      ELSE
       SININV = 0.0D0
      END IF
C  SET VALUES FOR N = 0, 1  (NMAX MUST BE AT LEAST 1)
      PMN(0,0) = 1.0D0
      PMN(1,0) = 0.0D0
      PMN(-1,0) = 0.0D0
      PMN(0,1) = X
      PMN(1,1) = -SINTHT
      PMN(-1,1) = SINTHT*0.5D0
C  IN LOOP, TNP1 = 2*N+1, TNP2FC = (2*N+2)!, M1N = (-1)**(N+1)
      TNP1 = 1.0D0
      TNP2FC = 2.0D0
      M1N = -1.0D0
      DO 4 N = 1, NMAX-1
       TNP1 = TNP1 + 2.0D0
       TNP2FC = TNP2FC * TNP1 * (TNP1+1)
       M1N = -M1N
       DO 3 M = -N, N
        PMN(M,N+1) = (TNP1*X*PMN(M,N) - (N+M)*PMN(M,N-1))/(N-M+1)
```

```
  3  CONTINUE
     PMN(N+1,N) = 0.0D0
     PMN(-N-1,N) = 0.0D0
     PMN(N+1,N+1) = (X*PMN(N,N+1) - TNP1*PMN(N,N)) * SININV
     PMN(-N-1,N+1) = M1N*PMN(N+1,N+1)/TNP2FC
  4 CONTINUE
C    DO 120 N=0,NMAX
C    DO 120 M=-N,N
C120  WRITE(6,130) N,M,PMN(M,N)
C130  FORMAT(1X,'  N= ' ,I4,1X,'  M= ' ,I4,1X,'  PMN= ' ,F13.6)
    RETURN
    END
```

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